ECONOMIC BENEFITS OF SHRP RESEARCH

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CHAPTER 1

ECONOMIC BENEFITS OF SHRP RESEARCH

INTRODUCTION

State highway departments conceived and funded the Strategic Highway Research Program (SHRP) to develop new technologies for designing and maintaining longer-lasting, safer roadways. The Strategic program identified six major areas of research: asphalt, long-term pavement performance, pavement maintenance, portland cement concrete and structures, snow and ice control and work zone safety. The study concluded that successful completion of the identified research would increase productivity of highway construction, reconstruction and rehabilitation and maintenance and would improve safety on the nations's highways.

This report assesses the economic benefits of these six areas of research. The basis for the economic assessment is a computer model developed at the Texas Transportation Institute (TTI). This model is explained in Chapter 2.

REPORT ORGANIZATION

This report contains eight chapters and eight appendices. Chapter 3 through 8 address the six SHRP areas of research. The second chapter explains the SHRP products produced, the approach to the economic assessment and the results of the economic assessment.

CHAPTER 2

METHODOLOGY FOR ASSESSING THE LIFE-CYCLE EFFECTS OF SHRP PRODUCTS

GENERAL PROCEDURE

The recommended procedure for estimating the life-cycle benefits for a SHRP research effort (project/product) includes the following activities.

1. Calculate the change in motorist benefits and agency costs for one or more typical implementation situations -- that is, for typical projects at one or more typical locations/situations where results are expected to be implemented. As the terminology is used here, benefits are usually of two types: (1) estimates of reductions in user costs associated with use of a new SHRP product and (2) estimates of reductions in agency costs associated with use of the new SHRP product. Depending on the specific approach used, these calculations will entail several assumptions and calculations as follows:

   a. Estimate or select service lives and/or analysis periods for each typical implementation situation or situations.

   b. Calculate agency costs with and without the use of the SHRP product for different typical situations. These costs should include the project-specific agency costs for this SHRP product, which are assumed to include all costs of implementation that can be attributed to use of the product at a specific location.

   c. Calculate motorist benefits as changes in motorist costs with and without the use of the SHRP product for different typical situations.

2. Estimate net benefit per implementation unit (e.g., mile of highway, location, ton, bridge, etc.).

3. Estimate the potential maximum number of implementation units that can be implemented and the time period over which implementation is assumed or expected to take place.

4. Select an expected/assumed implementation rate and an implementation period over which the research results are expected or assumed to be implemented.

5. Determine the research cost and non-specific-project implementation cost of the research effort (SHRP project/product). Non-project-specific costs are assumed to include, for example, general implementation costs at the federal, state and local levels of government, such as costs for implementation section personnel and costs of special training and equipment that support overall implementation of the specific SHRP product being analyzed.

6. Calculate the benefit-cost ratio for the SHRP project or product by dividing the total benefits by the sum of research and implementation costs.

BENEFITS AT A LOCATION

To calculate the benefits at a typical location when the new research-generated idea or approach will be implemented, select an analysis period, a discount rate and a technique for calculating reductions in agency and/or motorist (or user) costs.

Analysis Period

The analysis period should be a length of time sufficient to bring out the important costs and benefits being compared. This period may be the useful life of the improvement before it must be totally replaced or may be the length of time for which a traffic forecast is available and sufficiently trust worthy. For major highway improvements, this time period typically is 20 to 40 years. For minor improvements, it usually is 10 to 25 years.

Discount Rate

Several recent studies recommend a relatively low real discount rate. The *American Association of State Highway and Transportation Officials' Manual* on this topic recommends a rate of three to five percent. Since most benefits of research are to typical consumers (motorists), it is appropriate to use a rate that reflects the trade-off between the present and the future for these consumers. For benefit-cost analysis using benefits expressed in constant, non-inflated dollars, as in this study, researchers recommend that a five percent rate be used in calculating the benefits of research.

If the present worth of a series of benefits or costs is constant in each year, the present worth can be calculated using a uniform series present worth factor. If annual costs or benefits are not constant over time, the uniform series factors cannot be used. It sometimes is necessary to calculate the cost and benefit for each future year and discount each of these separately using the single payment present worth factor.

Technique for Calculating Motorist Benefits

Motorist benefits for the improved situation at a location using the new idea can be calculated as the reduction of the sum of the discounted present worth of motorist cost savings over the analysis period. Motorist benefits include reductions in vehicle operating costs travel time costs and accident costs calculated at a typical implementation location using the following formula:

$$PWMB = \sum_{t=1}^{N} PW_{i,t} (VOC_t + TC_t + AC_t) \qquad (1)$$

where:

PWMB	=	present worth of motorist benefits for the new research idea <u>in one location where it is implemented</u>, calculated over the analysis period,
N	=	length of the analysis period,
$PW_{i,t}$	=	single payment present worth factor for a discount rate i and year t; = $1/(1+i)^t$,
VOC_t	=	the reduction vehicle operating costs for the improvement using the new idea as compared to that the situation would have been without the new idea (the base condition),
TC_t	=	the reduction in time costs for the improvement using the new idea as compared to what the situation would have been without the new idea (the base condition), and
AC_t	=	the reduction in accident costs for the improvement using the new research idea as compared to what the situation would have been without the new idea (the base condition).

NET BENEFITS PER IMPLEMENTATION UNIT

Net Benefits at a Location

The net benefits (or net present value) for implementing research results at one location can be calculated as the present worth of benefits, calculated using equation (1), and the increase in cost from using the new research results:

$$NB = PWMB - (PWC_a - PWC_b) \tag{2}$$

where:

NB = the net benefits from implementing the research results at a location,

$PWMB$ = the present worth of motorist benefits at the location,

PWC_a = the present worth of agency cost at the location after implementing the research results, and

PWC_b = the present worth of agency cost at the location before implementing the research results.

The above formula assumes that the benefits and costs are estimated for a specific, typical location where research results apply. The expression in parentheses represents the increase in cost from using the research results. If there is a decrease in agency costs from implementing the research results, this value in parentheses is negative, in which case the savings in agency costs will be added to the present worth of benefits.

Some research efforts may yield research results that provide savings in agency costs but do not affect motorist benefits. The net benefits can be calculated with equation (3) by setting PWB equal to zero, in which case the equation (4) results and can be used to calculate the net benefits as savings in agency costs:

$$NB = -(PWC_a - PWC_b), \text{ or}$$

$$NB = PWC_b - PWC_a \tag{3}$$

where the variables are as defined previously. In making calculations of the benefits of research using different implementation rates, it often is desirable to convert the present worth of benefits, NB, to equivalent uniform annual benefits, EUAB, using the following definition.

$$EUAB = [crf(r,N)] \times NB \tag{4}$$

where:

EUAB	=	equivalent uniform annual benefit for one location (net of project-specific costs),
crf(r,N)	=	capital recovery factor for a discount rate r and an analysis period of N years, and
NB	=	present worth of benefits for one location, as defined previously.

Net Benefits Per Implementation Unit

It may be convenient to convert the estimate of annualized net benefits, NB, to net benefits per implementation unit, NBU, by dividing EUAB by the number of implementation units, U, at the location, as follows:

$$NBU = EUAB/U \tag{5}$$

where:

NBU	=	net benefits per implementation unit,
EUAB	=	annualized net benefits for the location, and
U	=	implementation units for the location for which research benefits are calculated.

For example, the location for which net benefits are calculated may consist of 20 lane miles of highway where the research results are implemented. It is desirable to convert the net benefits to net benefits per implementation unit, by dividing by the number of lane miles, or 20 lane miles. In practice, it may be possible to simply calculate the net benefits for one standard implementation unit
in the first place.

BENEFIT-COST RATIO FOR A RESEARCH AND IMPLEMENTATION EFFORT

To develop an estimate of total present worth of benefits for a research effort, two assumptions are made: (1) an analysis period over which the research results are assumed to be implemented is selected; and (2) an implementation rate for each year of that analysis period is assumed. Given this information together with the previously calculated benefits per implementation unit, the total present worth of benefits for an implementation effort is calculated as follows:

$$TPWB = \sum_{t=1}^{K} \{R_t \times M \times NBU\} \qquad (6)$$

where:

TPWB = total present worth of benefits for a research effort,

K = the length of the implementation period over which research results are expected to be implemented,

R_t = the rate (or cumulative proportion) of implementation units that are expected to be implemented through year t of the analysis period, and

M = the number of implementation units (e.g., lane miles of highway) for which the research results may be implemented, and

NBU = the equivalent uniform annual benefits per implementation unit, as defined previously.

The benefit-cost ratio for a research and implementation effort can be calculated by dividing the total present worth of benefits by the total cost of research and implementation for the research effort.

$$B/C = TPWB/(RC+IC) \qquad (7)$$

where:

B/C = the benefit/cost ratio for the total research and implementation effort,

TPWB = total present worth of benefits for a research effort (SHRP project/product) over the entire analysis period,

RC = the cost of the research effort, and

IC	=	the cost for implementing the results of the research effort (not including the project-specific costs that were considered in calculating net benefits per implementation unit).

An alternative formula that represents the benefit-cost ratio for the research effort alone can be calculated by subtracting the implementation cost from the numerator instead of adding it to the numerator:

$$B/C = (TPWB\text{-}IC)/RC \qquad (8)$$

where each variable is as previously defined.

In estimating the benefits of different SHRP research efforts, it was necessary to make assumptions about R_t, the rate (or cumulative proportion) of implementation units that are expected to be implemented through year t of the analysis period. In most cases, three different implementation scenarios apply. For example, it might be assumed that the implementation rate in the first year of the analysis period is quite low, typically 0.01 (or one percent) and increases to 0.50, 0.75, or 1.00 in the last year of the analysis period, depending on the scenario. An implementation rate of 1.0 (or 100 percent) represents full implementation of the research results, meaning the results are expected to be used in all potential implementation units (that is, all M units).

Calculation of PWB Using MicroBENCOST

In evaluating SHRP research projects/products, the MicroBENCOST computer program usually calculates the present worth of benefits for one implementation unit. This computer program is especially useful in this effort because it can be used for several different types of projects, including those that are expected to result in improvements in the serviceability index for pavements. The MicroBENCOST computer program represents an update, extension, and computerization of the American Association of State Highway and Transportation Office (AASHTO) procedure for benefit-cost analysis. A detailed description of the program is provided in appendix of this report.

The existing default data set for MicroBENCOST (Version 1.0, Revision A) was used except for updating the values of time and accident costs from 1990 to 1995 values. The updated values for these data items are shown in Tables 1, 2, and 3.

Table 1. Values of Time for Passenger Vehicles

Vehicle Description	**Value of Time ($/person-hour)**
Passenger Vehicles	
Small Passenger Car	$11.51
Med./Large Passenger Car	$11.51
Pickup/Van	$11.51
Buses	$12.56

Table 2. Values of Time for Trucks

Vehicle Description	Value of Time ($/vehicle-hour)
2-axle Single-unit Truck	$14.87
3-axle Single-unit Truck	$17.75
2-S2 Combination	$22.13
3-S2 Combination	$24.56
2-S1-2 Combination	$24.56
3-S2-2 Combination	$24.56
3-S2-4 Combination	$24.56

Table 3. Accident Costs

Accident Severity	Cost per Accident
Fatal Accident	$2,709,000.00
Injury Accident	$24,800.00
Property-damage-only Accident	$2,100.00

CHAPTER 3

LIFE CYCLE EFFECTS OF SHRP ASPHALT PRODUCTS

BACKGROUND

The United States spends about $15 billion annually on hot mix asphalt ($10 billion by the private sector). This is approximately 11 percent of total expenditures of $90 billion annually by the country's public highway agencies. Despite this large spending level on hot mix asphalt and the fact that more than 90 percent of our nation's hard-surfaced highways are paved with asphalt, relatively low levels of funding are spent on asphalt binder and asphalt-aggregate mixture research and development.

Problems with asphalt pavement performance, including rutting, fatigue cracking and low temperature cracking were influential in directing the SHRP research program to provide improved pavement performance by increasing the understanding of the chemical and physical properties of asphalt binders and hot mix asphalt materials.

This chapter assesses the benefits of the SHRP asphalt products which include the binder specifications, all levels of mixture design and characterization and Superpave performance modeling. This section briefly presents a qualitative assessment of the asphalt products. This is followed by more quantitative assessments based on case studies. Five case studies are presented: (1) the Texas Experience, (2) the Georgia Experience, (3) the Nevada Experience, (4) the National Center for Asphalt Technology Study and (5) the Zhang and Huber Study. Four of the case studies specifically address the binder specifications since binder specifications are the only SHRP asphalt product with sufficient time exposure for practical field evaluation.

The case studies provide insight for a realistic quantitative evaluation of the life cycle benefits of the SHRP binder specifications. No quantitative estimate was made of the effects of mixture testing or performance modeling due to the limited field exposure of these products. With the case studies as background, we estimate that the performance life of an asphalt surface mix will be increased by 50 percent from an average life of 8 years to an average life of 12 years.

The final section of this chapter is entitled "Cost Savings of Improved Binder Specifications"**.** The life cycle cost analysis presented in this section is based on the MicroBENCOST computer model and assumes a life cycle cost increase of 50 percent.

Qualitative Assessment

The Superpave system brings together performance based asphalt materials characterization and design environmental conditions to improve pavement performance by controlling rutting, fatigue cracking and low temperature cracking. The four major components of

Superpave are the asphalt binder specifications, mixture design and analysis system and a computer software system.

The Superpave asphalt binder specifications provide the ability to evaluate fundamental, performance related properties of binders at the temperatures and rates of loading which actually occur in the field. This is far different from either the penetration or viscosity based specifications for asphalt binders. The greatest improvement is that the SHRP binder specifications assess each distress mechanism at the temperature and rate of loading deemed critical for a specific environment. This, within itself, is a major and significant advancement over the traditional penetration or viscosity based specifications.

The Federal Highway Administration (FHWA) has promoted an aggressive program for implementation of the binder specification tests and the mixture design. This program is designed to aid in the effective transition toward the asphalt tests in a reasonable time frame.

Asphalt Binder Testing

The FHWA implementation program includes six major initiatives which will speed and assist the implementation of SHRP binder specifications.

- The purchase and loan of binder test equipment to asphalt user-producer groups for training and testing.
- The pooled fund effort in which states have pooled Federal-aid research money to purchase sets of testing equipment for Superpave binder and mixture specifications. In this effort contracts were awarded for equipment fabrication and delivery to the 52 participating agencies.
- The establishment of training courses in testing and analysis of data.
- The expansion of the Mobile Asphalt Laboratory to include the principles of Superpave volumetric mix design.
- The establishment of Superpave regional centers.
- The continuation of user-producer group coordination meetings.

Based on the FHWA implementation effort, it is reasonable to assume that the SHRP binder specifications will be fully implemented by all states within the next three to five years. At this level of implementation, considerable savings in the performance of asphalt pavements are expected.

Asphalt Mix Design

The FHWA program will also speed and assist in the implementation of the volumetric and level II and level III mix design programs. However, the implementation of these programs may be considerably longer than for the binder programs, perhaps three to ten years. This is based on several factors:

- the refinement of equipment and testing protocol still underway;
- further development and refinement of the Superpave performance models, and
- the complexity of mixture design compared to the relative simplicity of neat binder characterization.

TEXAS EXPERIENCE

Asphalt Sources in Texas and Associated PG Grades

The Texas Department of Transportation (TxDOT) has used the SHRP binder tests to characterize and grade the asphalts typically produced in Texas. Table 4 presents the performance grades of lab blended and production asphalt binders typically used in Texas. Table 4 lists 12 production asphalt binders used in Texas with the viscosity grade of AC-20. Seven of the 12 AC-20 production asphalts are listed as PG-64 binders. The remaining five are listed as PG-58 which is one high temperature grade level lower than PG-64.

Selection of Binder to Meet High Temperature Performance Requirements

Based on Table 4, if a PG-64 grade asphalt is required in Texas for high temperature performance, use of an AC-20 viscosity grade binder selected randomly from the 12 different suppliers will provide one PG grade level lower than that required for acceptable high temperature performance approximately 42 percent of the time. This use of one high temperature grade level lower than what is specified will result in a greater likelihood of pavement distress in the form of permanent deformation or rutting.

Obviously, refineries in various locations will endeavor to produce asphalts to meet the demands of the area. However, the point of this discussion is that selection of an asphalt based solely on viscosity or penetration grading is not definitive enough in terms of the rheological properties needed to assess performance.

According to SHRP specifications, a RTFOT aged binder must have a value of the parameter $G^* / \sin \delta$ of at least 2.2 kPa at the design high pavement temperature. This design high pavement temperature is determined by Superpave based on the average of the seven hottest days of the year. If one uses a typical generalized Burger model (Huang, 1993) for the viscoelastic response of asphalt binder, and if one applies time-temperature superposition to account for the temperature difference at which the value of 2.2 kPa is achieved, it is apparent that a PG-58 binder, if it meets the $G^*/ \sin \delta$ criteria exactly at 58^0 C, will have a significantly lower value of $G^*/ \sin \delta$ when tested at the design pavement temperature (i.e., 64^oC). The mathematical calculations indicate that the reduction in $G^*/\sin \delta$ will be about 50 percent. This mathematical approximation was verified by looking at typical dynamic shear rheometer data for several asphalts in the PG-58 to PG-64 range. The data indicate that a realistic approximation is that the

Table 4. TxDOT SHRP Testing Results on Production and Lab Blended Asphalt Binders

Material	**Production or Laboratory Blended**	**SHRP Performance Grade**
Calumet AC-20	Production	PG 58-34
Calumet AC-30	Production	PG 64-28
Calumet 30L3%	Lab Blended	PG 64-28
Calumet 45P	Lab Blended	PG 64-28
Chevron AC-5	Production	PG 52-28
Chevron AC-10	Production	PG 58-28
Chevron AC-20	Production	PG 58-28
Chevron 20L3%	Lab Blended	PG 64-28
Coastal AC-5	Production	PG 52-28
Coastal AC-10	Production	PG 58-28
Coastal AC-20	Production	PG 64-22
Coastal 5L2%	Production	PG 58-28
Coastal 5L3%	Production	PG 58-28
Coastal 10L2%	Production	PG 58-28
Coastal 20L3%	Lab Blended	PG 76-22
Cosden AC-10	Production	PG 58-22
Cosden AC-20	Production	PG 58-22
Cosden 5L2%	Production	PG 52-22
Cosden 10L3%	Production	PG 58-22
Cosden 20L3%	Lab Blended	PG 64-22
EAP MG-10/30	Production	PG 58-22
EAP MG-20/40	Production	PG 64-22
Ergon 45P	Production	PG 64-22

Table 4. TxDOT SHRP Testing Results on Production and Lab Blended Asphalt Binders (cont'd)

Material	Production or Laboratory Blended	SHRP Performance Grade
Exxon AC-5	Production	PG52-2
Exxon AC-10	Production	PG 52-28
Exxon AC-20	Production	PG 58-22
Exxon 20L3%	Lab Blended	PG 64-22
GSA AC-5	Production	PG 52-28
GSA AC-20	Production	PG 64-22
GSA 20L3%	Lab Blended	PG 64-22
GSA 15P	Production	PG 58-28
GSA 30P	Production	PG 64-22
GSA 45P	Production	PG 64-22
GSA EVA	Production	PG 58-22
KM AC-5	Production	PG 52-28
KM AC-10	Production	PG 58-28
KM AC-20	Production	PG 64-22
Koch 15P	Production	PG 58-28
Koch 45P	Production	PG 70-28
Lion AC-10	Production	PG 58-28
Lion AC-20	Production	PG 58-22
Lion 20L3%	Lab Blended	PG 70-22
NW AC-5	Production	PG 52-34
NW AC-10	Production	PG 58-28
NW AC-20	Production	PG 64-28
NW 30L3%	Lab Blended	PG 64-22

Table 4. TxDOT SHRP Testing Results on Production and Lab Blended Asphalt Binders (cont'd)

Material	**Production or Laboratory Blended**	**SHRP Performance Grade**
NW 15-5TR	Production	PG 58-28
Shamrock AC-10	Production	PG 58-22
Shamrock AC-20	Production	PG 64-22
Shamrock 5L2%	Production	PG 58-22
TFA AC-10	Production	PG 58-28
TFA AC-20	Production	PG 64-22
TFA AC-30	Production	PG 64-22
TFA 5L2%	Production	PG 58-28
TFA 10L2%	Production	PG 58-28
TFA 20L2%	Production	PG 70-22
TFA 15-5TR	Production	PG 64-28
Total AC-5	Production	PG 52-28
Total AC-10	Production	PG 58-22
Total AC-20	Production	PG 64-22
Total 20L3%	Lab Blended	PG 70-22
Trumbull 5L2%	Production	PG 52-28
Trumbull EVA	Production	PG 64-22
West Houston AC-2	Production	PG 64-22

$G^*/\sin\delta$ value decreases by approximately 50 percent for every 6^0C increase in testing temperature.

Anderson and Kennedy (1993) presented data which relate $G^*/\sin\delta$ to rut depth based on testing accomplished with the Hamburg device, Figure 1. According to these data, a reduction of $G^*/\sin\delta$ for a binder when tested at 60^0 C and at 10 rad/sec from 2.2 kPa to 1.5 kPa results in a rut depth increase of from about 65 mm to about 150 mm. These data are based on 20,000 cycles of the Hamburg device at 50^0 C. If one continues to evaluate the changes in rutting based on changes in $G^*/\sin\delta$, it is apparent that a rutting potential approximately doubles for each 50 percent reduction in $G^*/\sin\delta$ and hence for each 6^0 C increase in test temperature. Therefore, based on typical and realistic data, missing the desired high temperature performance grade by one level (i.e., supplying a PG-58 in lieu of a PG-64) can result in significantly larger rut depths.

Table 5 presents $G^*/\sin\delta$ v. temperature for all available data on sources of AC-20 binders in Texas. Based on these data and on the reduction of $G^*/\sin\delta$ with increase in temperature, a reasonable assumption for an approximate analysis of the effects of binder selection on rutting performance is that a 6^0 C increase in temperature increases rutting potential by 100 percent, a 40^0C increase in temperature increases rutting potential by 67 percent and a 2^0C increase in temperature increases rutting potential by 33 percent. Obviously, rutting at high temperature is primarily controlled by mix characteristics and not binder properties. Therefore, this relative approximation of the effects of the binder is dependent on the mix used and is only a very rough approximation. Furthermore, if a mix is designed to be rut-resistant based on its aggregate matrix, the ultimate rutting may be very little, i.e., 5-mm or less. Therefore, a 33 percent increase is still a very low level of rutting, i.e., 6.7-mm.

Selection of Binders to Meet Low Temperature Performance Requirements

SHRP criteria require a binder to have a stiffness of less than 300 MPA and a slope of the stiffness versus time of loading curve of no more than 0.30 at 60 seconds of loading using the Bending Beam Rheometer (BBR) when tested at the design, minimum pavement temperature. Kandahl et al. (1995) verified that these are reasonable criteria based on the performance of six AC-20 asphalt cements in Pennsylvania. Performance of these six projects was monitored over a 7-year period.

Data from these six projects are listed as T1 through T6 in Figure 2. This figure presents the binder stiffness value on the ordinate and the slope, m, on the abscissa. If the locus of these two points for any binder plot falls within the dashed box, cracking should not occur with at least a 50 percent level of reliability in this climatic area of Pennsylvania. Pavements T1 and T5 cracked severely and within a period of a few months. Pavements T3 and T4 cracked longitudinally but did not demonstrate transverse cracking typical of thermally-induced cracking.

Although sufficient data are not available to predict the frequency or severity of transverse cracking based on BBR relative test results, one can judge that meeting BBR criteria at the lowest

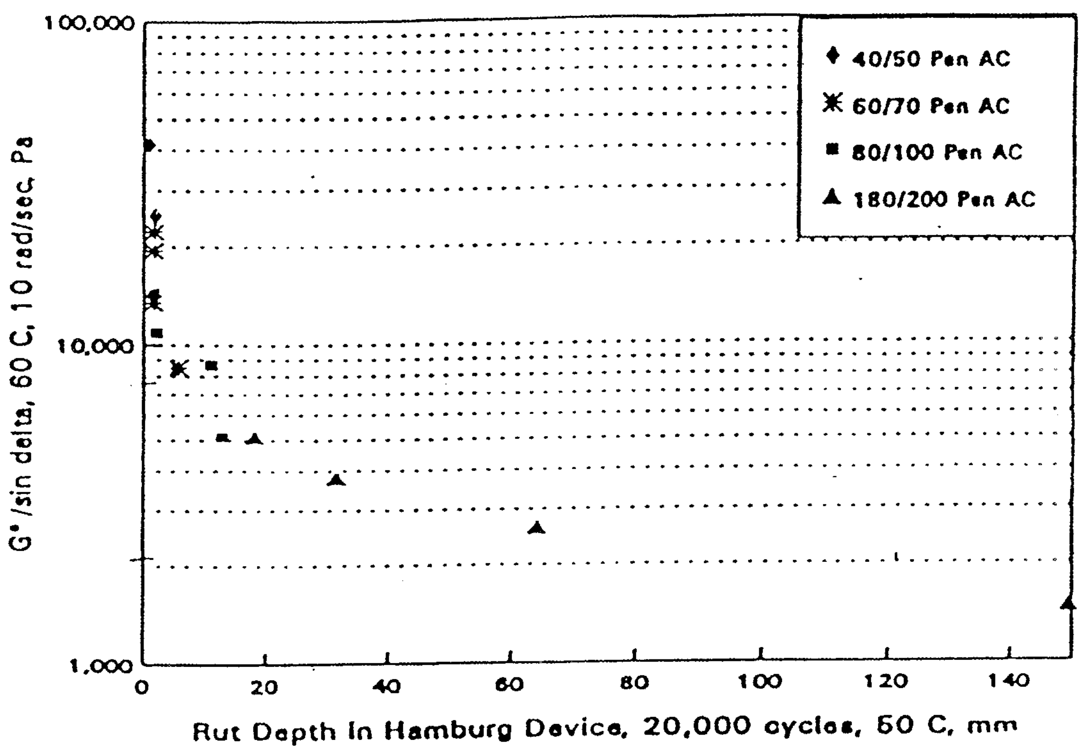

Figure 1. Dynamic Oscillatory Shear vs. Hamburg Device Rut Depth. After Anderson and Kennedy, 1993

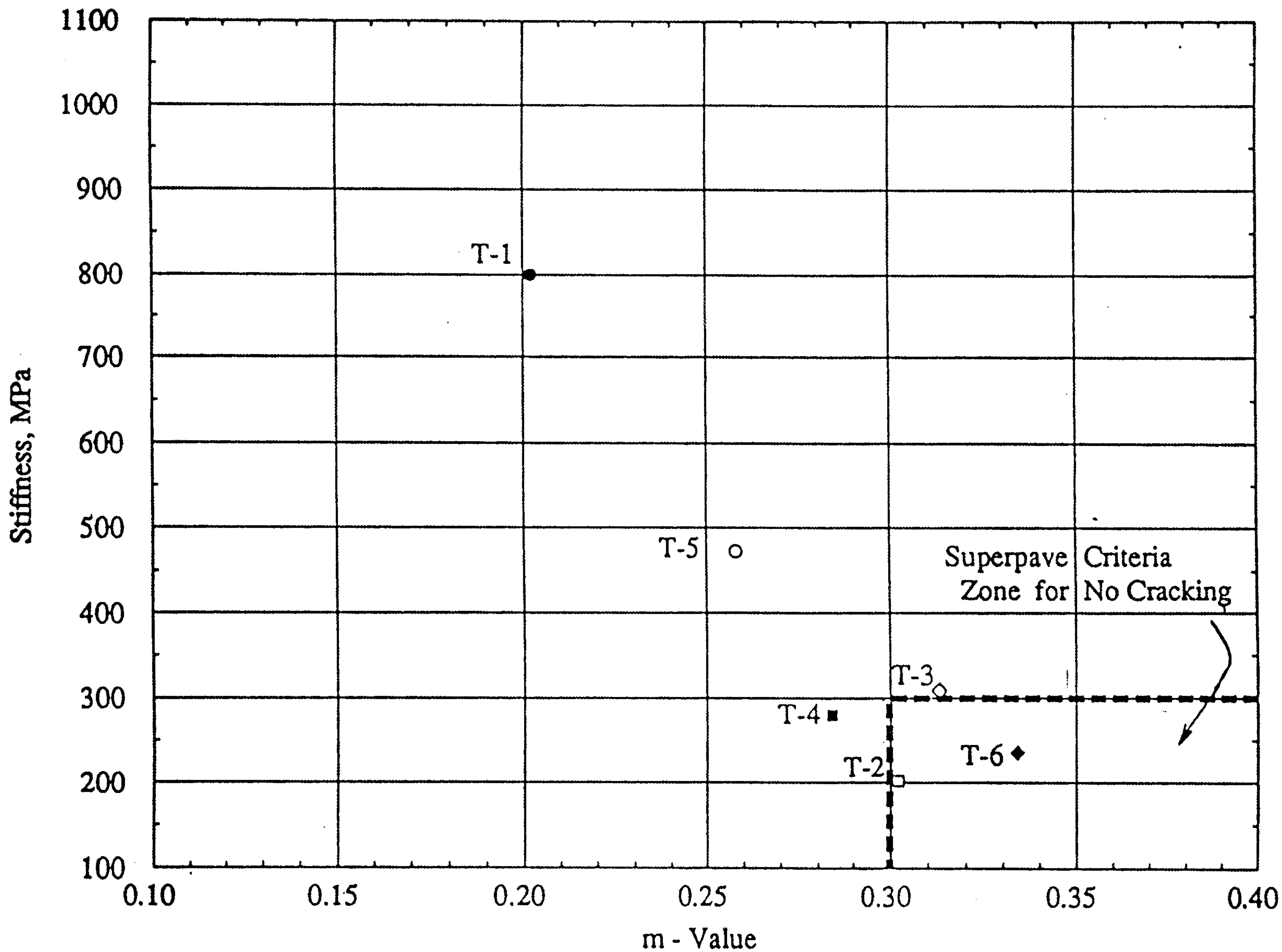

Figure 2. Creep Stiffness and Creep Slope for Six Pennsylvania Asphalts

Table 5. Relationship Between G*/sin δ for Typical Asphalts.

G*/sin δ (RTFO Residue) kPa				
Temperature, C	**Citco AC-10**	**Citco AC-20**	**Texaco AC-20**	**SBS-Modified AC-10**
58	7.36	13.10	5.00	
64	3.33	6.00	2.25	
70	1.55	2.78	1.00	
76	0.75	1.31	1.12	5.26
82				2.91
88				1.63
94			0.15	0.92

winter (design) temperature at a 50 percent reliability level can make a difference between severe thermal cracking and no significant cracking. Since the stiffness of the binder is logically related to severity of thermal cracking, and this is demonstrated in Figure 2 of the Pennsylvania data, higher degrees of reliability should be associated with lower levels of severity of thermal cracking. The selected scale for evaluation is that if the low temperature PG grade is above the 50 percent reliability low temperature, the potential for thermal cracking is severe. If the low temperature PG grade is one standard deviation below the 50 percentile low temperature, the potential for thermal cracking is moderate, and if the low temperature PG grade is two standard deviations below the 50 percentile low temperature, the potential for thermal cracking is very low.

Selection of Binders to Meet Intermediate Temperature Performance Requirements

In order to meet PG grade requirements, a binder must have a value of G* sin δ below 5 MPa at the design intermediate pavement temperature. This parameter is the shear loss modulus and was shown by Hicks et al. (1993) to be directly related to dissipated energy during controlled stress flexural fatigue testing. Hicks et al. (1993) presented a relationship between G* sin δ and number of cycles to fatigue failure. This relationship is shown in Figure 3 and was used as an approximate prediction of the effect of variation in G* sin δ on flexural fatigue life.

TxDOT Assessment of Reliability of Current Methods of Binder Selection

In a separate analysis, Mr. Darren Hazlett of the Materials and Tests Division of TxDOT estimated that 25 percent of the use of asphalt binders in Texas is not correct for the environmental conditions of the location. Although this 25 percent is an estimate, it is supported by data from 396 weather stations in Texas where the effect of selecting one “lesser” performance grade (i.e., PG-58 in lieu of PG-64) for high temperature performance and one lesser performance grade (i.e., PG-m-16 in lieu of PG-m-22) for low temperature considerations was evaluated. This effect is represented in Table 6 where such data are taken for 16 representative weather stations throughout the State of Texas from the list of 396 stations. Here it can clearly be seen that the selection of one lesser grade has a very substantial effect on the confidence level.

For example, in the case of the Alice weather station in Jim Wells County, the required PG high temperature grade is 64 for a 98 percent reliability. Selection of one lesser high temperature grade reduces the confidence level of selecting the correct binder from 98 percent to 1.83 percent. For the same station, using one lesser grade low temperature binder decreases the confidence level from 98 percent to only 50 percent.

A more definitive example of the effect of proper binder selection to avert low temperature problems in the Texas Panhandle was also articulated by Hazlett. This area of the state predominately uses asphalt from one producer. The PG grade of this AC-20 is PG 58-22. For Amarillo, this yields confidence limits of 68 percent and 82 percent for distresses associated with high and low temperatures, respectively. For Dalhart, also in the Panhandle where thermal cracking is a long-time and severe problem, the corresponding confidence limits are 70 percent and 60 percent for distresses associated with high temperature and low temperature, respectively. This means that Superpave predicts a very high likelihood of thermal cracking for the binder normally used in this area. According to Hazlet, the expected life of pavements in the Amarillo and Dalhart areas are 5 and 1.5 years, respectively.

The conclusion is that with the asphalt binders currently produced in Texas, random selection of a binder based solely on viscosity grading is likely to result in either high temperature distress or low temperature distress or both.

A closer study of the 396 weather stations in Texas reveals that for a 98 percent confidence level 62 locations require a high temperature PG grade of 70, 366 require a high temperature PG grade of 64 and the other 9 require a high temperature PG grade of 58. For 95 percent confidence the respective numbers are 21 for PG-70, 366 for PG-64 and 9 for PG-58. A statistical evaluation of data from the 396 weather stations reveals that providing one lesser high temperature grade level results in an average confidence level of only about 28 percent.

Based on the data from the 396 stations in Texas, at the 95 percent confidence level, 98 percent require a high temperature grade level of at least PG-64. Thus random selection of AC-20 binders from the production sources presented in Table 4 could result in selection of one lesser high temperature grade binder about 41 percent of the time.

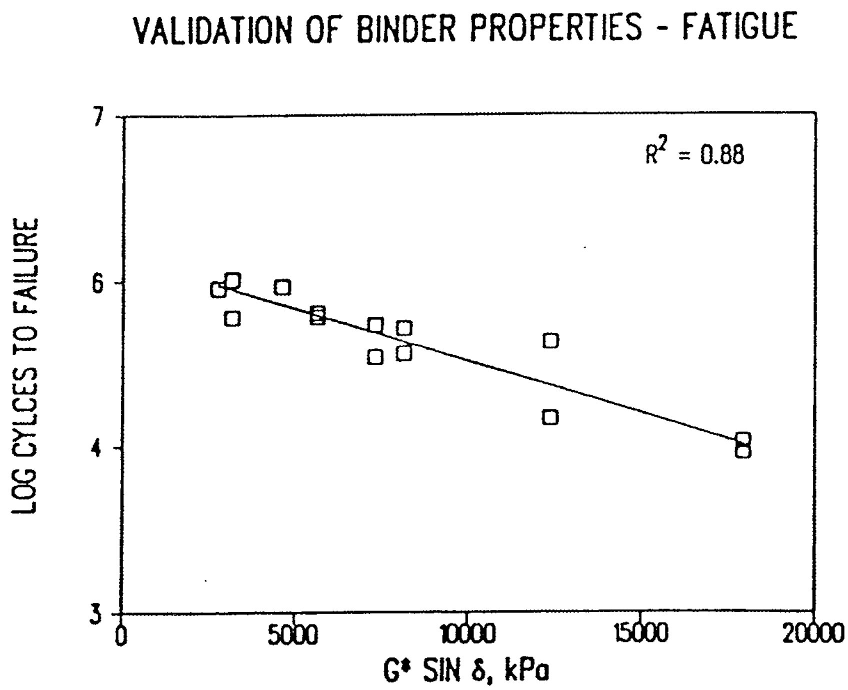

Figure 3. Relationship Between Dissipated Energy (signified by G* sin δ) and Number of Load Applications to Flexural Fatigue Failure.

Table 6. SHRP Design Maximum High 7-Day and Low Temperatures for Selected Weather Stations in Texas (98% Reliability) and the Effect of Selecting One Lesser SHRP Grade Binder.

Station	Longitude	Latitude	High Temp., ºC	Low Temp.,ºC	H-1 Confidence Level	L-1 Confidence Level
Alice	98	32	64	-10	2	50
Austin WSO	98	30	64	-16	18	82
Baytown	95	30	64	-16	77	89
Borger	101	36	64	-28	48	89
Bracket-ville	100	29	64	-16	3	86
Browns-ville	97	26	64	-10	29	86
Childress	100	34	64	-22	22	73
College Station	96	30	64	-16	28	73
Crockett	95	32	64	-16	30	62
Del Rio	101	29	64	-16	3	97
Elgin	97	30	64	-16	4	64
Lubbock WSFO	102	34	64	-28	39	97
Lufkin WSFO	95	31	64	-28	30	60
San Antonio WSFO	98	30	64	-16	26	73
Amarillo WSO AP	102	35	64	-28	86*	82*
Dalhart FAA AP	103	36	64	-34	70*	60*

* Confidence level associated with use of PG 58-22

The effect of selecting one lesser low temperature grade in Texas is less dramatic but is still quite significant. Of the 396 weather stations in Texas, at a 95 percent confidence level, 25 require a low temperature grade of -28, 190 require a low temperature grade of -22, 142 require a low temperature grade of -16, 39 require a low temperature grade of -10 and the remaining 1 requires a low temperature grade of -4. Missing the required low temperature grade by one low temperature grade level reduces the confidence level from 95 percent to about 75 percent.

TxDOT Estimate of Cost and Benefits of Superpave Implementation

TxDOT estimates that approximately $2.2 billion can be saved in Texas over a 30 year period by selecting the correct binder all the time using PG criteria. This will eliminate selection of the wrong binder approximately 25 percent of the time. This estimate accounts for the Superpave equipment costs, record keeping and yearly costs for equipment maintenance and general upgrading. This estimate is based on a cost increase of asphalt cement from $70 per ton to $100 per ton caused by the new SHRP testing and specifications. The offsetting factor is that TxDOT assumes an overlay performance life increase from 8 years to 12 years based on proper binder selection.

As a further breakdown, the TxDOT estimate is that Superpave will save Texas $65,000 per lane mile over the next 30 years. With the assumption that 25 percent of the lane miles in Texas will be affected, the $2.2 billion savings is calculated. The total cost estimate for SHRP equipment and support over the 30 year period is $470 million. The resultant benefit to cost ratio is 468.

The estimate of a 50 percent increase in performance life for the 25 percent of pavements in Texas for which the wrong binder is selected is reasonable based on estimates of selection of one lesser grade of binder for high temperature performance.

Evaluation of Potential Cost Savings for Selected TxDOT Districts

Six districts within TxDOT were selected to compare the effects of selection of the AC-20 binders typically used within the district based on Superpave binder grading of the binders (PG grading). These six districts were selected because each has predominately two sources of asphalt supply, Table 7. Both sources are AC-20 binders. However, the SHRP binder tests reveal that the binders are, in most cases, significantly rheologically different. The actual test temperatures at which the critical SHRP rheological criteria which correlate to rutting, fatigue and low temperature cracking are presented in Table 8.

Table 9 presents the binder sources for the six districts selected and documents the test temperature difference between the two binders, T, at which a critical SHRP binder specification is met. For example, in the case of the Paris District, two sources of binder are available: Total and Lion. Column three of Table 9 identifies that the temperature at which the value of G*/sin δ for the two RTFOT-aged binders drops below the critical value of 2.2 kPa. This occurs for the

Total binder at 65^0 C and for the Lion binder at 63^0 C. Hence, the difference recorded in Table 8, column three is 2^0 C. Columns four and five reflect T's for thermal cracking (based on values of creep stiffness and creep slope) and load-associated fatigue (based on G* sin δ).

Paris District (1)

The Paris District typically uses AC-20 binder from two sources: Total and Lion. These two binders, Table 8, meet G*/ sin δ criteria at 65^0 C and 63^0 C, respectively. The two binders meet G* sin δ criteria up to 18^0 and 21^0 C, respectively. Both binders meet low temperature creep stiffness and creep slope criteria at -12^0 C. Hence, the Total binder has superior high and intermediate temperature properties. Since the 98 percentile 7-day maximum temperature in Paris is 64^0 C, the Total binder should satisfy these conditions virtually all the time. However, the Lion asphalt will rut approximately 33 percent more severely at a the design temperature (64^0 C) than will the Total binder. Based on the difference in dissipated energy as approximated by G* sin δ, Figure 3, the total binder will probably fatigue crack more severely. Based on the fatigue relationship between G* sin δ and fatigue life, Figure 3, the severity of fatigue cracking is approximately 7 percent greater for asphalt produced with the Lion binder than with the Total binder at approximately the average annual pavement temperature for the District.

A reasonable performance model of the life of an asphalt concrete overlay or pavement surface is based on the ultimate level and rate of distress caused by rutting, load-associated cracking and thermal cracking. The differences in the relative performances of the two sources of asphalt in the Paris District indicate the potential for a significantly different performance and consequently a significantly different serviceability life. Based on the predictions of potential difference in rutting, load-induced cracking and thermal cracking a reasonable difference in serviceable life for a typical overlay in the Paris District when comparing the two binders, Total v. Lion is very significant. For example an overlay constructed with the Total binder could feasibly last 12 years whereas an similar overlay with the Lion binder may last only 8 years.

The approximate differential in performance lives between the two binders is based on a worst case scenario. Since the binders are usually selected with a high level of reliability, usually 95 or 98 percent, the SHRP criteria should not be compromised for either binder and the binder should function satisfactorily. However, the relative differences in the two binders over the entire temperature spectrum indicate improved relative performance from mixes with the Total binder in the Paris District. The relative difference in the basic parameters G*/sin δ, G* sin δ and creep stiffness and creep slope across the spectrum of reasonable performance temperatures is the basis for the assessment of potential differences in relative performance. This assertion is backed by the data presented in Figures 4 through 11 where critical SHRP rheological parameters are plotted for each Texas asphalt as a function of temperature.

The SHRP binder specifications offer the ability to differentiate based on relative difference in distress potential. This is not the case for viscosity-based specifications.

Table 7. TxDOT Asphalt Use by District.

District	Asphalt Suppliers	District	Asphalt Suppliers
Paris	Total Lion	Austin	Texas Fuel and Asphalt Coastal Exxon Gulf States West Houston Asphalt Star
Fort Worth	Total Coastal Exxon Fina BS		
Wichita Falls	Kerr-McGee Coastal Total	San Antonio	Coastal Texas Fuel and Asphalt Exxon
Amarillo	Diamond Shamrock Fina BS	Corpus Christi	Coastal Texas Fuel and Asphalt
Lubbock	Diamond Shamrock Fina BS	Bryan	Fina BS Exxon Neste/Wright West Houston Asphalt
Odessa	Fina BS Chevron		
San Angelo	Coastal Fina	Dallas	Total Fina Coastal Kerr McGee Exxon
Abilene	Fina BS Total Coastal		
Waco	Fina Neste/Wright Exxon West Houston Asphalt Coastal Gulf States Total	Atlanta	Lion Kerr McGee Exxon
		Beaumont	Exxon Coastal West Houston Asphalt
Tyler	Fina BS Lion West Houston Asphalt Gulf States Kerr McGee	Pharr	Texas Fuel and Asphalt Coastal Trifinery Coastal
		Laredo	Coastal
Lufkin	West Houston Asphalt Neste/Wright Exxon Coastal Gulf	Brownwood	Fina Coastal Texas Fuel And Asphalt Chevron
		El Paso	Chevron Fina

Table 7. TxDOT Asphalt Use by District.

District	Asphalt Suppliers	District	Asphalt Suppliers
Houston	Neste/Wright West Houston Asphalt Exxon Coastal	Childress	Diamond Shamrock Fina Kerr McGee Coastal Total
Yoakum	Coastal Neste/Wright		

Table 8. Actual Temperature at which PG Criteria are met in Texas Asphalts.

Binder	G*/sin δ =2.2 kPa (RTFOT Residue)	G*sin δ=5 MPa (PAV Residue)	Creep Stiffness $\leq$ 300 MPA (PAV Residue)	Creep Slope $\leq$ 0.30 (PAV Residue)
Calumet	64	8	-30	-23
Chevron	61	12	-30	-18
Coastal	66	20	-19	-12
Fina	65	13	-14	-12
Exxon	63	19	-15	-16
GSA	63	19	-13	-13
K. McGee	65	19	-18	-12
Lion	63	21	-15	-12
Neste Wright	67	19	-19	-18
Shamrock	63	21	-16	-12
TC&A	65	21	-15	-13
TOTAL	65	18	-17	-12

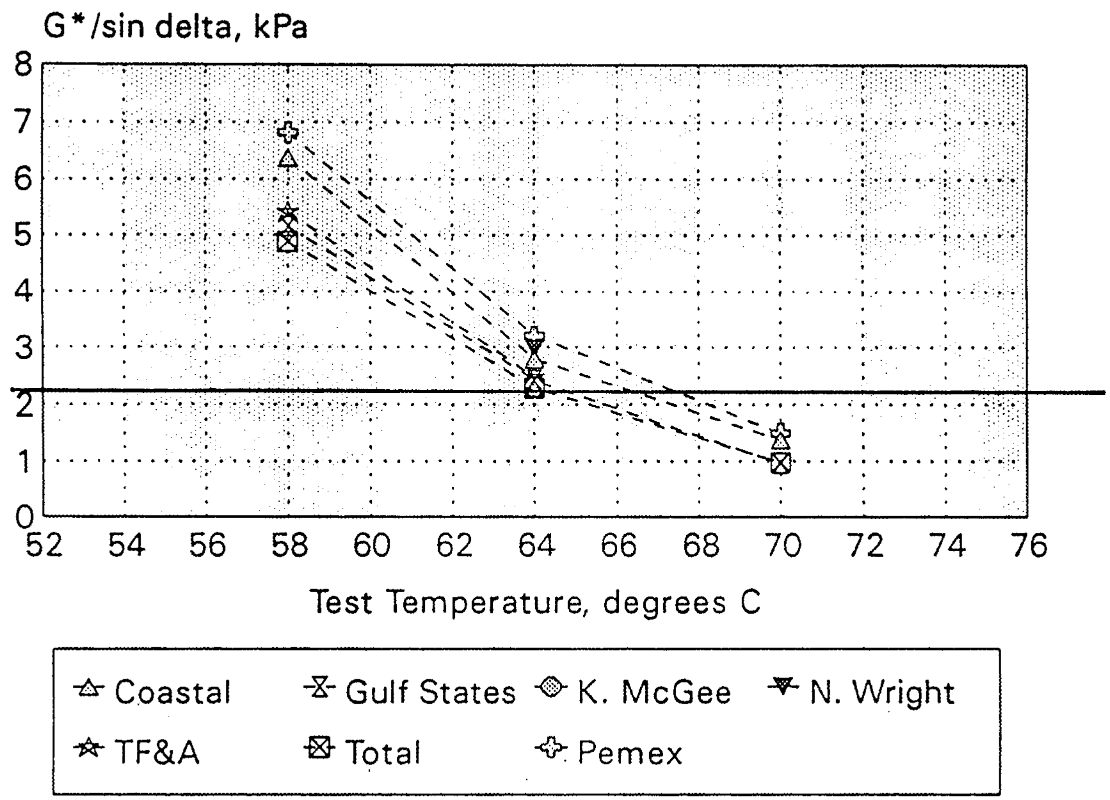

Figure 4. Relationship Between G*/sinδ for RTFOT Residue and Temperature for Texas Asphalts Classified as GP-64.

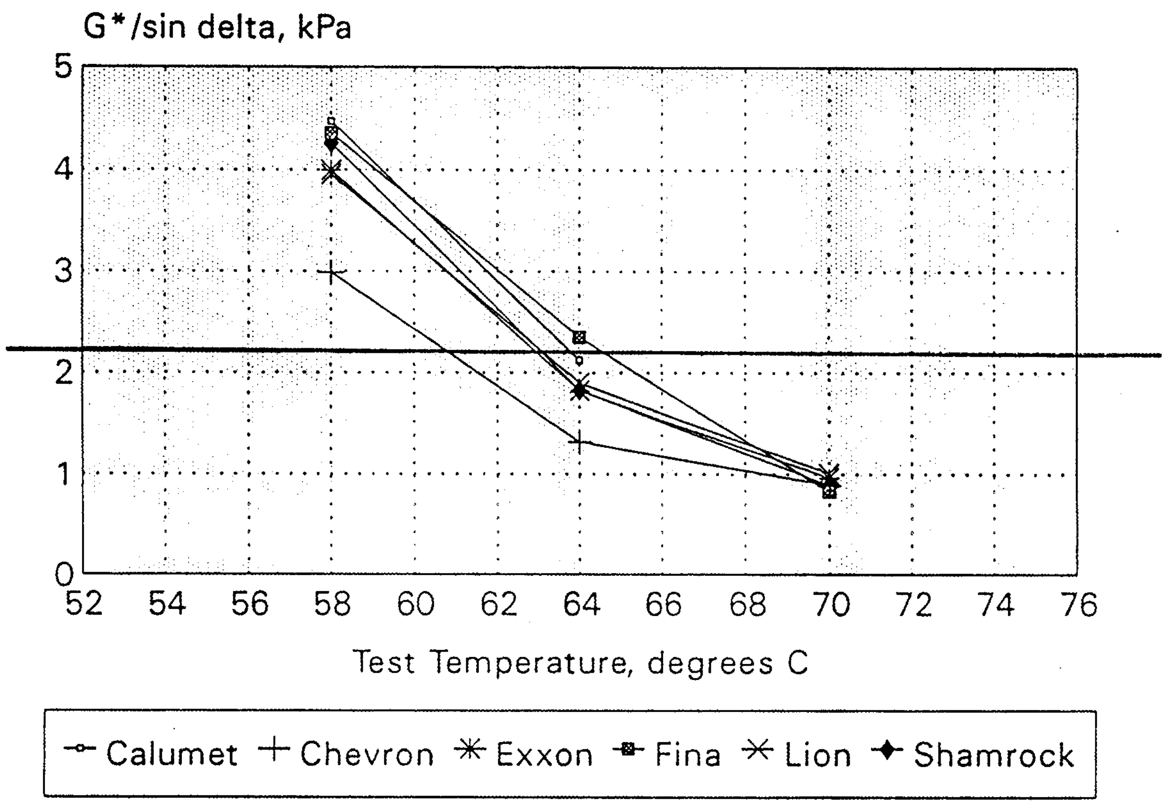

Figure 5. Relationship Between G*/ sinδ for RTFOT Residue and Temperature for Texas Asphalts Classified as PG-56.

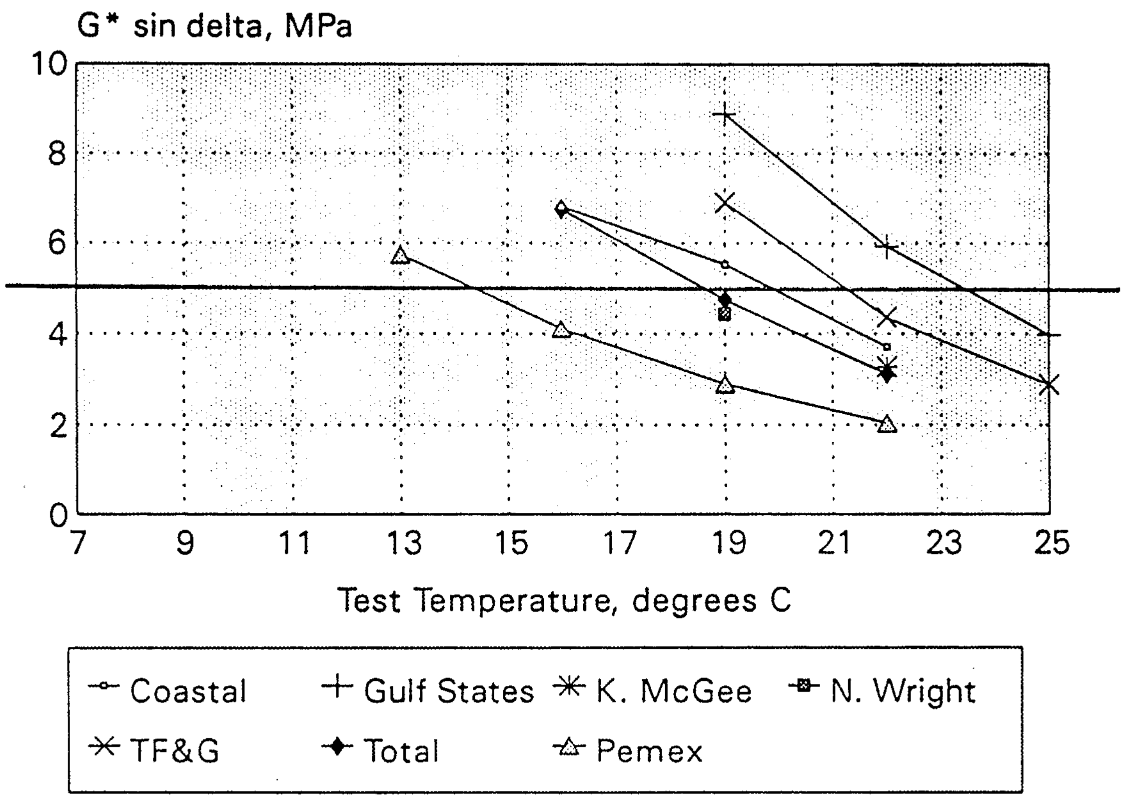

Figure 6. Relationship Between G* sinδ for PAV Residue and Temperature for Texas Asphalts Classified as PG-64.

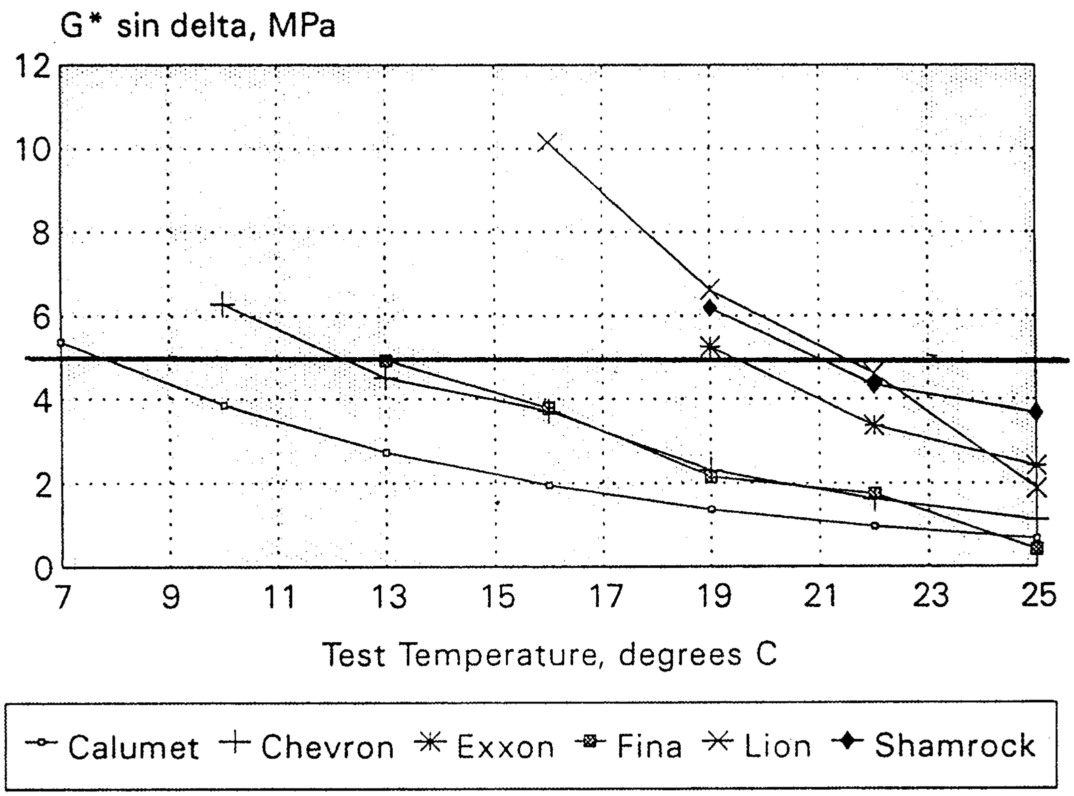

Figure 7. Relationship Between G* sin δ for PAV Residue and Temperature for Texas Asphalts Classified as PG-58.

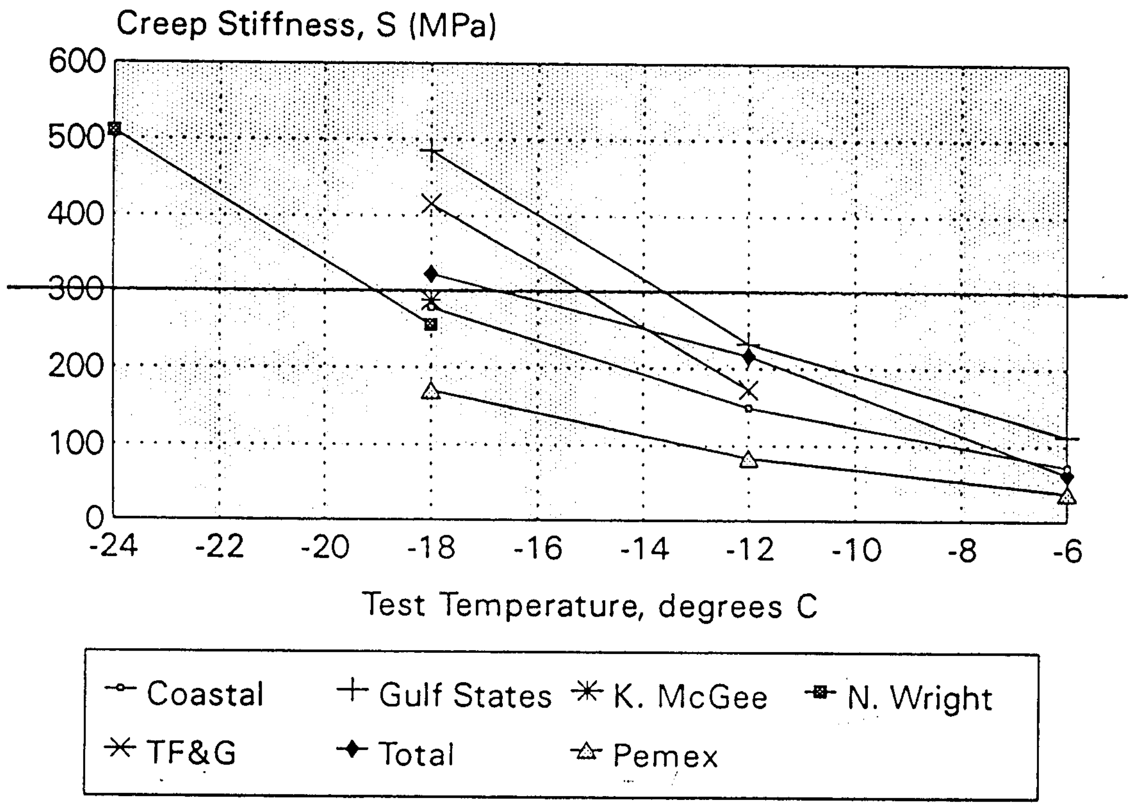

Figure 8. Relationship Between Creep Stiffness for PAV Residue and Temperature for Texas Asphalts Classified as PG-64.

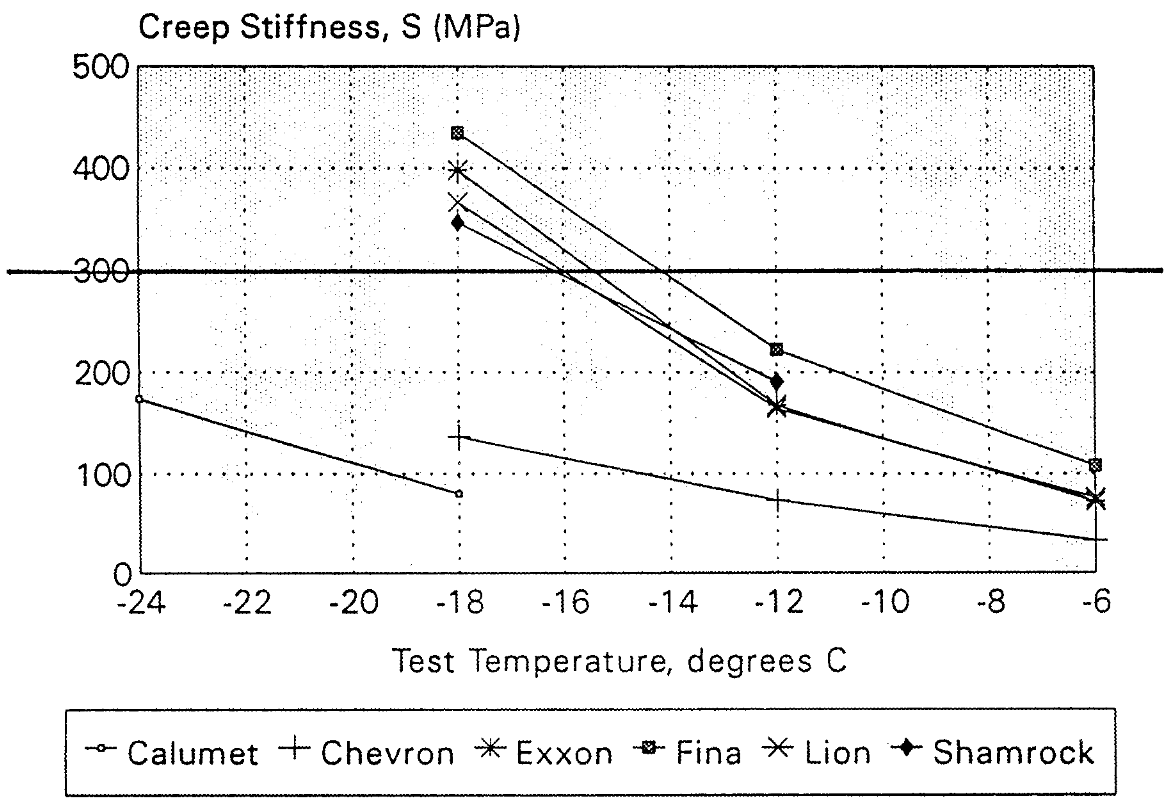

Figure 9. Relationship Between Creep Stiffness for PAV Residue and Temperature for Texas Asphalts Classified as PG-58.

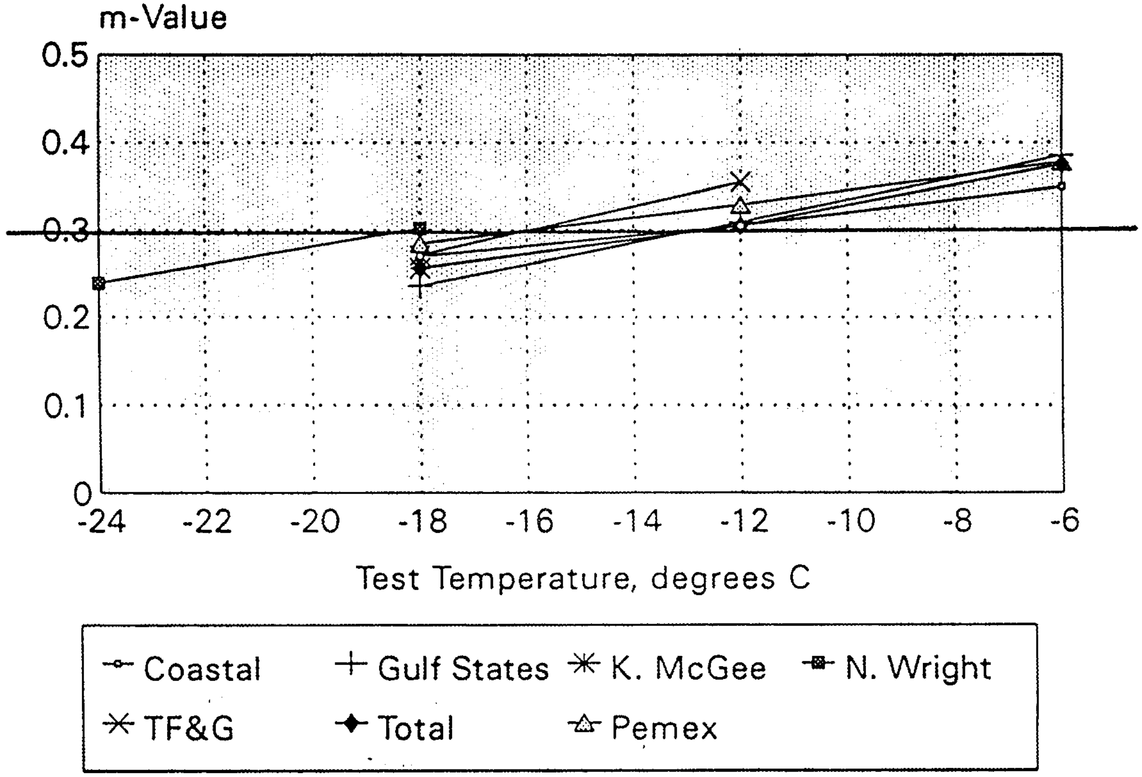

Figure 10. Relationship Between M-Value for PAV Residue and Temperature for Texas Asphalts Classified as PG-64.

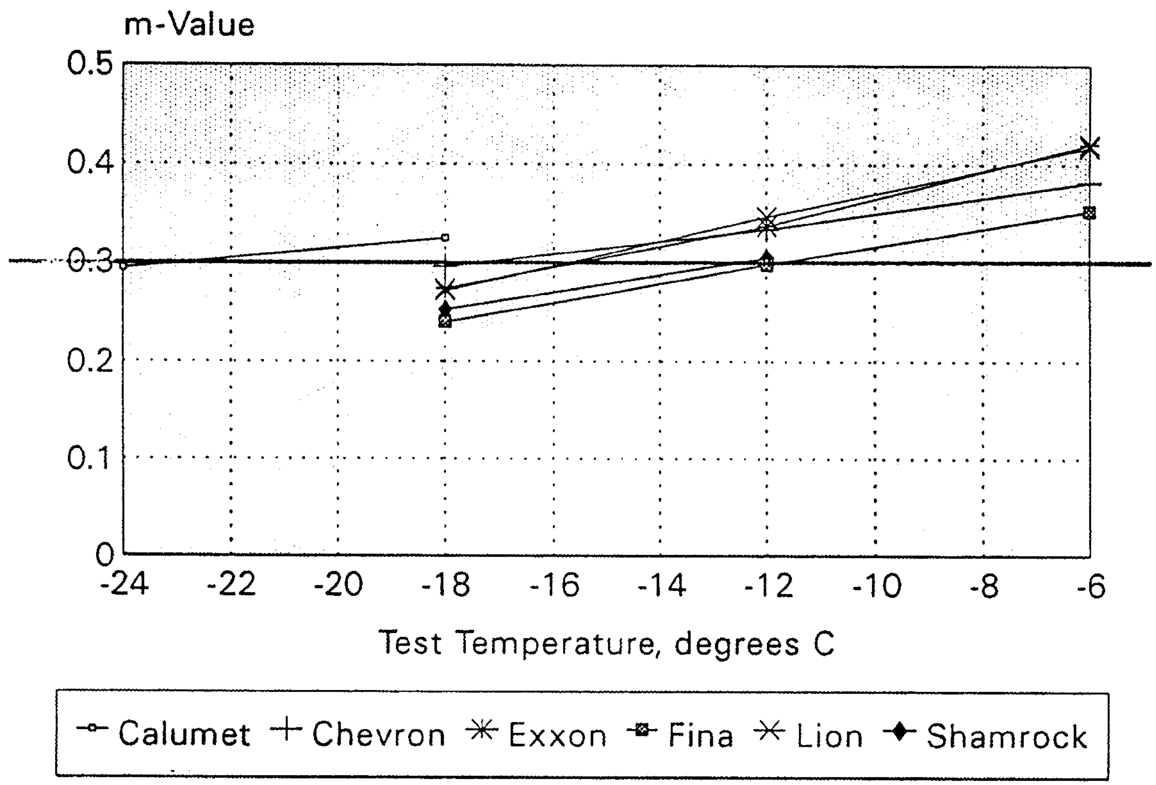

Figure 11. Relationship Between M-Value for PAV Residue and Temperature for Texas Asphalts Classified as PG-58. Other Districts

Other Districts

The other five district for which these comparisons were made are listed in Table 9. Table 9 lists the asphalt sources in column two and the relative differences in temperature at which critical SHRP parameters are determined in columns three through five. The effect of these relative differences in rheological responses are summarized in Table 10.

Case History Demonstrating the Use of Superpave Practice to Identify Cost Effective Asphalt Modification in Texas

The SHRP research effort has provided a separate practice for the evaluation of modification of asphalt binders. This practice is designated as AASHTO PP5. It provides the means to: (1) pinpoint the need for modifier use during the mix design process, (2) estimate the performance capacity of modified asphalt binders and paving mixtures under specific climatic and traffic conditions, (3) perform simple cost comparisons of modified v. unmodified asphalt binders and paving mixtures over extended periods of service and (4) suggest an appropriate modifier for a given situation. This protocol was recently used to evaluate the effects of several modifiers and two different mix types for use by TxDOT. This testing for TxDOT was performed by Advanced Asphalt Technologies of Sterling, Virginia.

The base asphalt in the study was a Citco AC-10. Three types of polymer modifiers were evaluated: low density polyethylene (LDPE), styrene-butadiene-styrene (SBS) and layex styrene-butadiene-rubber (SBR). Two different mixes were considered: a typical dense-graded surface course mix (Texas Item 340) and a coarse mastic-high binder mix (CMHB).

The first phase of the analysis used SHRP binder specification tests to determine the PG grade of the Citco AC-10 binder with different levels of modification (0, 2, 4 and 6 percent). The results of this testing are summarized in Table 11.

The binder testing clearly differentiates the effects of the three polymer additives on the base asphalt. As is normally true in Texas, a major objective of modification in this case was to improve the high temperature resistance of the binder to deformation (rutting). Latex SBR is a popular additive for this purpose. The binder tests show that the additive level typically used in Texas (2 to 4 percent) is ineffective in changing either the high or low temperature performance of the base asphalt according to SHRP binder tests. On the other hand, LDPE and SBS shift the high temperature grading by one grade level at the 4 percent additive rate and by two grade levels at the 6 percent additive rate.

Based on the binder study, the SBS and LDPE polymer at an additive rate of 6 percent by weight of binder were used with three different asphalt cements typically used in Texas: Cosden AC-10, Total Petroleum AC-10 and Exxon AC-10. Two different mix types were considered: a dense-graded Item 340 mix and a coarse mastic-high binder content mix (CMHB). The results of the SHRP mix screening test (repeated shear test with constant stress ratio) for the Item 340 mix

Table 9. Comparisons of Temperature at which Binders Meet SHRP Criteria.

District	Binder Sources Available	Rutting T^1	Thermal Fracture T^2	Load - Associated Fatigue, T^3
Paris	Total Lion	2	0	3
Amarillo	Shamrock Fina	2	2	8
Lubbock	Shamrock Fina	2	2	8
Odessa	Fina Chevron	4	16	1
San Angelo	Fina Coastal	1	3	7
El Paso	Fina Chevron	4	20	1

Notes: T^1 - Temperature difference between the two source binders at which G*/sinδ 2.2 KPa is achieved.

T^2 - Temperature difference between the two source binders at which critical stiffness is exceeded or critical slope is compounded.

T^3 - Temperature difference between the two source binders at which G* sin δ = 5 MPA is exceeded.

are presented in Figure 12 while the results of the repeated shear testing for the CMHB mix are presented in Figure 13.

The data from the SHRP binder tests and from the simple repeated load shear test are important and significant in that they clearly demonstrate which binders and mix types should be selected to minimize permanent deformation at high pavement temperatures and the level of additive required to provide cost effective results. These findings are based on rational engineering properties of the binder and the mix and provide a level of prioritization which could not have been determined using penetration or viscosity testing of the binder or simply from traditional mix design testing such as that used in the Marshall or Hveem methods.

Specifically, the pertinent findings from this case history are:

1. Low levels of SBS or SBR solids have little effect on the performance grade at eight high or low temperatures. Taken together with the mix results, these data suggest that the use of low levels of any modifier will have little effect on the resistance of the pavement to rutting. Any specification that permits the use of less than 4 percent of a polymeric modifier in the binder for a dense-graded mix may not be cost effective and should be carefully evaluated.

2. Based on an upper limit of 2 percent permanent shear strain, the CMHB mix provides the best rutting resistance regardless of the asphalt binder used; however, the use of unmodified AC-10 yields substantially higher levels of permanent shear strain compared to the modified binders regardless of mix design.

3. Elimination of ineffective modification of asphalt binders has the potential for very significant cost savings. The addition of a polymer typically increases the cost of a ton of hot mix by between $5 and $10. For illustration, we will take the higher number and assume that 10 percent of the hot mix in Texas is modified every year. Further assume that 25 percent of the time an ineffective modification is used either because the wrong additive is selected or because too little modifier was used in the binder. If this ineffective use could be eliminated by Superpave as shown in the preceding example, the cost savings in Texas would be approximately $600 million over a 30 year period. This calculation assumes the production of approximately 600 millions tons of hot mix over a 30 year period in Texas.

Summary of Texas Experience

Six districts within Texas in which two sources of asphalt are typically used were selected for investigation. It can be demonstrated that even though each binder is classified as an AC-20 based on viscosity based classification, the binders in some cases have significantly different rheological properties. The different rheological response can, in some cases, result in significant differences in performance. These relative differences are summarized in Table 7 and are differentiated into the categories of rutting, fatigue cracking and low temperature cracking.

Although the relative differences are, in some cases, substantial, the differences in mixture performance, especially in the case of rutting, are difficult, if not impossible, to assess based solely on binder properties. Therefore, the relative assessment of level of rutting presented in Table 10 may not be of much practical consequence if the aggregate matrix of the mix is designed to resist rutting so that ultimate rutting is low regardless of the binder rheology. On the other hand, a poorly designed aggregate matrix may be quite sensitive to binder selection and the relative differences recorded in Table 10 may be significant.

We believe that the relative differences in performance recorded in Table 10 for fatigue and low temperature cracking are much more binder dependent and hence more relevant to SHRP binder evaluation.

In order to establish the differentiation between or among candidate binders as done in this section, it is necessary to perform SHRP binder tests at least three different temperatures that bracket the critical pavement or pavement design temperature. This is illustrated in Figures 4 through 11.

The ability of SHRP binder parameters to differentiate among binders in a specific region based on performance predictions is even more significant when one considers that suppliers in a specific region have attempted to meet regional requirements for a successful binder. The SHRP binder specifications make this task easier for supplier and user and can significantly shorten the period of product evolution to meet performance requirements.

Table 10. Relative Reduction In Performance Life Due to Selection of Lesser Binder Within the Six Test Districts of Texas.

District	**Relative Reduction in Performance Life Due to Selection of Lesser Binder**		
	Rutting Based on G*/sin δ	**Load-Induced Fatigue Based on G*sin δ**	**Thermal Cracking Based on Creep Stiffness and Creep Slope**
Paris	33% - Ultimate level of rut-susceptibility is low for either binder	7% - Fatigue potential is low for either binder	No significant thermal cracking for either binder
Amarillo	33% - Ultimate level of rut-susceptibility is low for either binder	6% - Fatigue potential is moderate for Shamrock and low for Fina	Severe thermal cracking for each binder
Lubbock	33% - Ultimate level of rut-susceptibility is low for either binder	6% - Fatigue potential is moderate for Shamrock and low for Fina	Severe thermal cracking for each binder
Odessa	67% - Rut-susceptibility for Fina binder is low; Rut susceptibility for Chevron binder is high	5% - Fatigue potential is low for either binder	Severe thermal cracking for Fina binder; No significant thermal cracking for Chevron binder
San Angelo	16% - Ultimate level of rut-susceptibility is low for either binder	13% - Fatigue potential is low for either binder	No significant thermal cracking for either binder
El Paso	67% - Rut - susceptibility for Fina binder is low; Rut susceptibility for Chevron binder is high	0% - Fatigue potential is very low for either binder	No significant thermal cracking for either binder

Table 11. SHRP Performance Grades for Various Levels of Modification of a Citco AC-10 Binder with Three Different Polymer Additives.

Percent Modifier	**Citco AC-10 with Polymer Additives**		
	LDPE	**SBS**	**SBR**
0	PG 58-28	PG 58-28	PG 58-28
2	--	PG 58-28	PG 58-28
4	PG 64-28	PG 64-28	PG 58-28
6	PG 70-28	PG 70-28	--

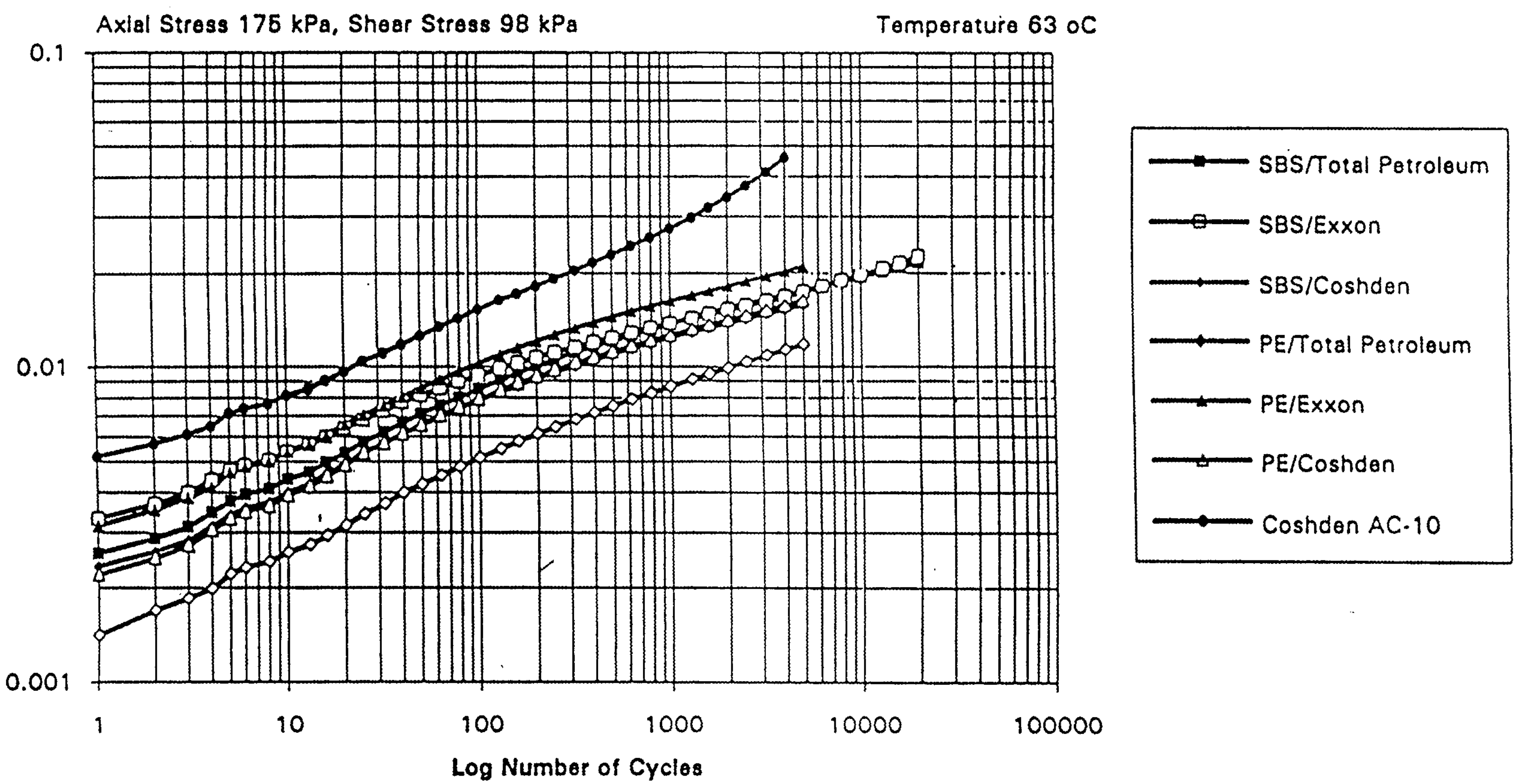

Figure 12. Repeated Shear Load Induced Deformation vs. Number of Loading Cycles for Texas 340 Mix Type with Various Binder.

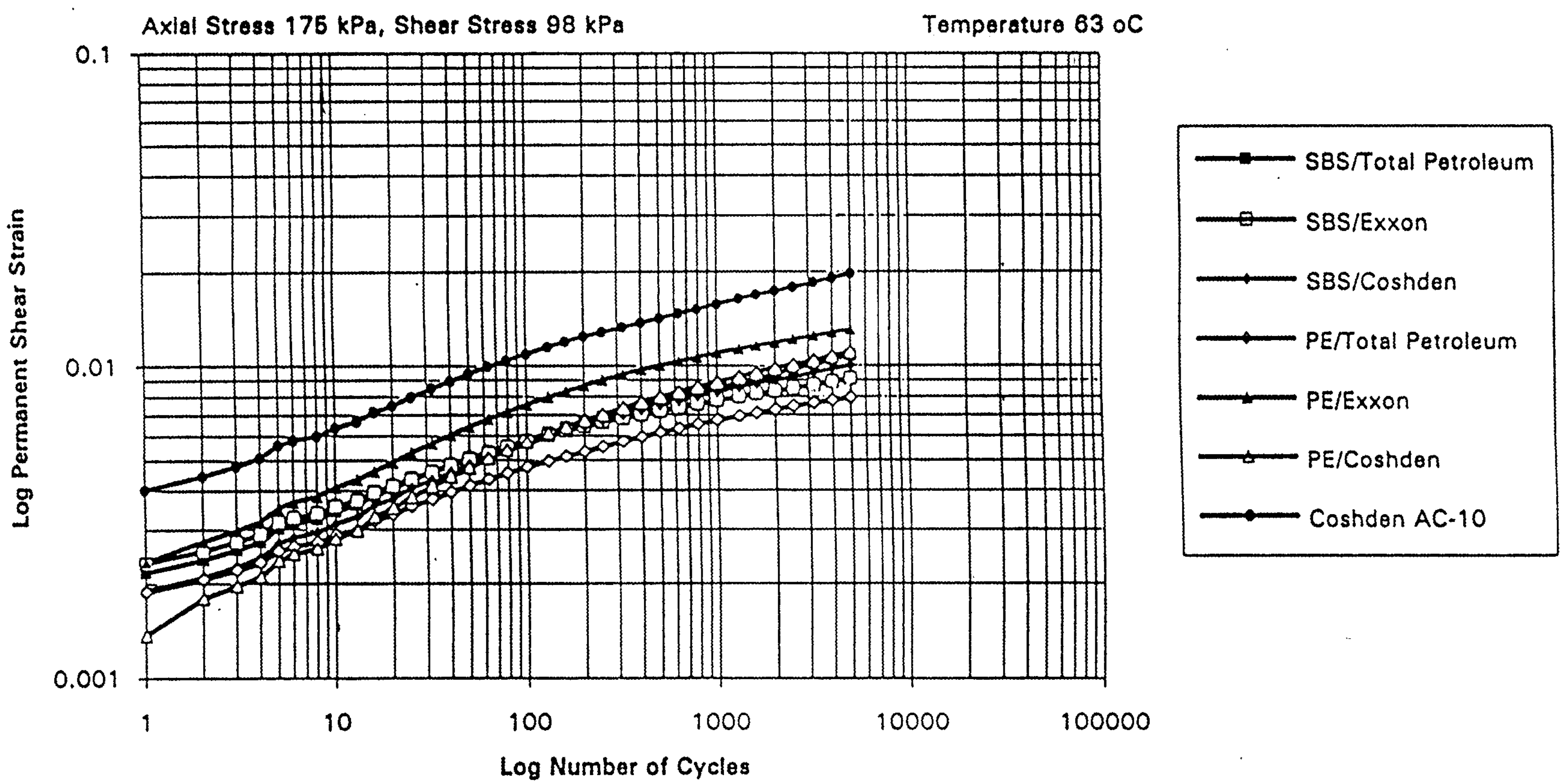

Figure 13. Repeated Shear Load Induced Deformation vs. Number of Loading Cycles for MMHB Mix Type with Various Binder types.

GEORGIA EXPERIENCE

Asphalt Sources in Georgia

In 1995 Georgia used approximately 37,800,000 tons of AC-30 binder, approximately 29,900,000 tons of AC-20 binder and approximately 600,000 tons of AC-10 binder. Approximately 2,100,000 tons of polymer modified asphalt cement was used in Georgia. The suppliers of these asphalts are summarized in Table 12.

Table 12. Suppliers of Asphalts Used in Georgia in 1995.

Asphalt Supplier	Location	Asphalt Grade	Approximate Quantity Supplied, Tons
Ergon	Bainbridge	AC-30	7,796,453
		AC-20	2,233,605
		AC-10	339,328
Citgo	Savannah	AC-30	9,596,504
		AC-20	820,983
		AC-10	33,207
Coastal	Candler	AC-30	5,444,434
		AC-20	164,103
Koch	Savannah	AC-30	4,170,723
		AC-20	858,436
		AC-10	191,730
Amoco	Doraville	AC-30	1,613,857
		AC-20	2,268,438
		PMAC	1,330,846
Coastal	Atlanta	AC-30	2,677,239
		AC-20	1,595,288

Table 12. Suppliers of Asphalts Used in Georgia in 1995 (cont'd).

Asphalt Supplier	Location	Asphalt Grade	Approximate Quantity Supplied, Tons
Shell	Lithonia	PMAC	774,191
Amoco	Atlanta	AC-30	2,605,121
Coastal	Pensacola	AC-30	1,193,427
		AC-20	770,366
Amoco	Chattanooga	AC-30	1,229,225
		AC-20	134,290
Coastal	Mobile	AC-30	1,202,125
		AC-20	143,894
Marathon	Jacksonville	AC-30	83,073
		AC-20	1,176,110
Coastal	Jacksonville	AC-30	34,517
		AC-20	107,020
Coastal	St. Marks	AC-30	109,047

Performance Grade Requirements for Georgia

Approximately **% of the state of Georgia requires a performance grade of PG 64-22 to satisfy a 98 percent level of reliability. A performance grade of PG 58-16 is required to satisfy a 50 percent level of reliability.

In order to investigate the critical SHRP rheological properties of typical Georgia asphalts, Georgia Department Of Transportation (GDOT) identified the four AC-30 and two AC-20 binders most frequently used in Georgia. The pertinent SHRP rheological properties of these binders, identified as A through F, are given in Table 12

Table 13. Values of Critical SHRP Rheological Properties for Most Commonly Used Georgia Asphalts.

Asphalt	Grade	Assessment of Rutting Potential on RTFOT Residue		Assessment of Fatigue Cracking Potential on PAV Residue		Assessment of Thermal Cracking Potential on PAV Residue		
		Test Temp, C	G*/ sin δ	Test Temp. C	G* sin δ	Test Temp. C	Creep Stiffness MPa	Creep Slope
A	AC-30	64	2.30	22	4.56	-12	257	0.34
B	AC-30	64	3.48	19	4.73	-18	307	0.32
C	AC-30	64	3.12	19	4.86	-18	324	0.34
D	AC-20	64	2.30	22	3.20	-18	414	0.33
E	AC-30	64	2.79	22	4.97	-12	263	0.33
F	AC-20	64	2.78	22	4.50	-18	85	0.30

All of the six Georgia asphalts tested met PG 64-22 criteria. However, some rate better than others according to the critical SHRP rheological parameters. The order of rank is listed in Table 14.

Table 14. Order of Rank of Six Georgia Asphalts from Best (Top) to Worst (Bottom).

G*/ sin δ on Original Binder (Rutting)	G*/ sin δ on RTFOT Residue (Rutting)	G* sin δ on PAV Residue (Fatigue)	Flexural Creep on PAV Residue (Thermal Cracking)
B	B	F	F
C	C	B	B
E	E	C	C
D	F	D	D
F	A	A	A
A	D	E	E

General Conclusions of Binder Performance Based on SHRP Binder Tests

SHRP binder testing showed the following general conclusions.

1. Asphalt B is an AC-30 that is extensively used in Georgia. This asphalt is rated best of the six based on original and RTFOT binder testing and is rated second based on predicted pavement aging (PAV) properties.

2. Asphalt C is also an AC-30 used extensively in Georgia. This asphalt rated second among the six based on original and RTFOT binder testing and third among the six on the basis of testing PAV-aged binders.

3. Asphalt E is an AC-30 that has not been extensively used in Georgia. This asphalt has a 56 dmm penetration and does not meet the minimum 60 dmm pen established in the Georgia Specification 820.01. This sample rated third of the six asphalts for initial SHRP characteristics; however, it rated poorest of the six asphalts in terms of predicted fatigue and thermal cracking potential where the PAV-aged binder was tested.

4. Asphalt F is an AC-20 that has a penetration of 96 dmm. This asphalt was a primary paving asphalt used prior to Georgia's adopting AC-30 grade asphalts. Elimination of this high penetration asphalt was expected to help reduce rutting of Georgia pavements. This sample rated fifth among the six when original binder samples were tested for $G^*/ \sin \delta$, fourth on the basis of $G^*/ \sin \delta$ on RTFOT residue and best among the six asphalts on $G^* \sin \delta$ and creep stiffness testing on PAV residue samples.

5. Asphalt A is an AC-20 asphalt and is rated sixth and fifth based on testing of original binder and RTFOT testing. It rated fifth among the six based on the test results of PAV residue samples.

6. Asphalt D is an AC-20. It rated fourth and sixth, respectively, based on testing of original binder and RTFOT residue and fourth based on testing of PAV residue.

Asphalts B and C, both AC-30s, rank one and two, respectively, in terms of the rheological property $G^*/ \sin \delta$ when measured on the RTFOT residue. This is an indication of rutting potential. These binders rank two and three, respectively, in terms of fatigue potential as approximated by $G^* \sin \delta$ and based on low temperature cracking potential as approximated based on creep stiffness and creep slope (when measured on PAV residue). This is an intriguing find since AC-30s, though more resistant to rutting at high performance temperatures, are usually more susceptible to cracking, either in the form of fatigue or thermal fracture. However, asphalts B and C outperform AC-20 asphalts A and D both in terms of rutting potential and in terms of fracture potential. Only asphalt F (an AC-20) ranks above asphalts B and C in terms of fracture potential. However, this binder ranks last in terms of rutting potential approximation based on RTFOT residue testing.

This case history illustrates how SHRP binder specifications and evaluation methodology clearly differentiate among performance potential of candidate binders and how this ranking is substantiated through performance.

Using the evaluation methodology discussed under the section entitled, “Texas Experience,” the relative potential of each binder to suffer distress in a typical dense-graded mix is summarized in Table 15.

Table 15. Prediction of Relative Performance Among Six Georgia Asphalts in a PG 64-22 Climate Compared to Asphalt B (Reference - Control).

Asphalt	**Relative Potential to Suffer Distress:**	
	Rutting Based on $G^*/\sin\delta$ on RTFOT Residue	**Fatigue Cracking Based on $G^*\sin\delta$ on PAV Residue**
B (AC-30)	Reference	Reference
C (AC-30)	20% increase	No difference
E (AC-30)	40% increase	5% increase
F (AC-20)	40% increase	15% reduction
A (AC-20)	66% increase	No difference
D (AC-20)	66% increase	7% reduction

Finally, it is important to note that the SHRP binder tests, as summarized in Table 15, demonstrate the validity of the decision to go with an AC-30 asphalt binder in Georgia. Based on this analysis, it is logical to estimate that moving from an AC-20 to an AC-30 binder, and more specifically AC-30 binders like B and C, would significantly reduce rutting without significantly sacrificing the ability of the pavement to resist fatigue and thermal fracture. A rational approximation of increased pavement overlay life in Georgia based on selection an optimum binder, such as B or C, is 25 percent.

NEVADA EXPERIENCE

Background

The Nevada Department of Transportation (NDOT) used 74,000, 117,000 and 118,000 tons of asphalt binders in 1993, 1994 and 1995, respectively, on highway projects. Table 15 summarizes the distribution of asphalt cements among the various grades.

Nevada is one of several western states that has begun implementing performance based asphalt specifications (PBA) proposed by the Pacific Coast user/producer group. In fact Nevada is currently considering whether the optimal solution would be to blend the PBA and SHRP binder grading system.

The University of Nevada at Reno prepared a report to NDOT in December of 1995 in which selected asphalt binders typically used in Nevada were characterized according to SHRP binder testing protocol and classified according to SHRP binder specifications. Twenty asphalts in use in construction projects throughout the state were selected for characterization. The combination of this testing with eventual field performance data will provide an opportunity to verify SHRP's binder specification system.

NDOT Study to Evaluate SHRP Classification of 20 Binders Used in Actual Construction Projects in Nevada

Table 17 presents the contract number (representing a specific contract and location), the SHRP grade of the asphalt used for that contract and the binder grade for the specific location based on a 50 percent and 98 percent level of reliability. The data for the grade requirements were provided by the SUPERPAVE software and are based on 72 weather stations throughout the state of Nevada.

The grading data in Table 17 indicate that if the SUPERPAVE recommendations are used, four of the AC-20Ps (2544, 2545, 2558 and 2611), two AC-30's (2501 and 2604), AC-20+TLA (2603), AC-40 (2604) and both AC-30P (2622-1 and 2622-2) would meet the requirements under the 50 percent reliability criteria. If the SUPERPAVE 98 percent reliability recommendations is used, the AC-20+TLA (2603), one AC-30 (2604) and both AC-30Ps (2622) would meet the requirements of the projects. The majority of the binders (16 out of 23) met the low temperature requirements of the projects at the 50 percent level.

Table 18 presents the actual temperature at which each binder evaluated fails ($G^*/\sin\delta$ goes below 2.2 kPa) the rheological parameter used to evaluate high temperature rutting. Table 18 presents the actual temperature at which each binder fails ($G^* \sin\delta$ exceeds 5.0 MPa) the rheological parameter used to evaluated the potential for flexural fatigue.

Based on the information in Tables 17 through 19, Table 20 summarizes the potential of each binder to experience distress within the climatic region associated with each of the twenty construction projects.

Table 16. NDOT 1993 and 1994 Asphalt Binder Quantities.

Asphalt Type	Quantity (Tons) 1993	1994	1995
AC-10	3,958	9,381	5,245
AC-10R	NA	5,707	NA
AC-20	17,957	27,167	16,950
AC-20+TLA	NA	913	NA
AC-20P	51,424	70,093	71,416
AC-30	668	2,548	24,195
CRM	NA	1,392	203
Total	74,007	117,201	118,009

Table 17. Recommended Binder Grades Based on SUPERPAVE Data Base.

Contract Number	AC Grade	SHRP Grade	SUPERPAVE 50% Reliability	SUPERPAVE 98% Reliability
2480	AC20-P	PG58-28	PG64-16	PG70-22
2491	AC-20P	PG-52-16	PG58-28	PG64-40
2501	AC-30	PG64-16	PG64-10	PG70-16
2501	AC-20P	PG58-28	PG64-10	PG70-16
2530	AC-20P	PG58-28	PG64-10	PG70-16
2544	AC-20P	PG58-28	PG58-28	PG64-40
2545	AC-20P	PG58-22	PG58-22	PG64-28
2552	AC-20P	PG58-28	PG70-16	PG70-22
2558-93	AC-20P	PG58-22	PG58-22	PG64-28
2558-94	AC-20P	PG58-16	PG58-22	PG64-28
2591	AC-20P	PG58-16	PG58-28	PG64-40
2594	AC-20P	PG58-28	PG64-10	PG64-16
2603	AC-20+TLA	PG70-16	PG64-10	PG70-16
2604-1	AC-40	PG64-10	PG64-10	PG70-16
2604-2	AC-30	PG70-22	PG64-10	PG70-16
2611-1	AC-20	PG64-16	PG58-28	PG58-40
2611-2	AC-20P	PG64-28	PG58-28	PG58-40
2615	AC-20P	PG58-28	PG58-34	PG58-40
2617	AC-20P	PG52-22	PG64-16	PG64-28
2622-1	AC-30P	PG70-22	PG64-10	PG70-16
2622-2	AC-30P	PG70-16	PG64-10	PG70-16

Table 18. Actual Temperature at Which the Value of G*/Sinδ Falls Below 2.2 kPa.

Contract	Binder	Temperature (^{0}C) at G*sin (d) = 2.2 kPa	High Temperature Grade
N/A	AC-20	67.5	PG64
N/A	AC-20	68.3	PG64
2480	AC-20P	63.0	PG58
2491	AC-20P	57.8	PG52
2501	AC-30	69.8	PG64
2501	AC-20P	63.2	PG58
2530	AC-20P	63.6	PG58
3544	AC-20P	63.0	PG58
3545	AC-20P	58.4	PG58
2552	AC-20P	63.0	PG58
2558-93	AC-20P	58.7	PG58
2558-94	AC-20P	56.5	PG52
2591	AC-20P	62.6	PG58
2594	AC-20P	63.3	PG58
2603	AC-20+TLA	72.6	PG70
2604	AC-40	68.6	PG64
2604	AC-30P	70.0	PG70
2611	AC-20	66.7	PG64
2611	AC-20P	65.2	PG64
2615	AC-20P	62.5	PG58
2617	AC-20P	57.9	PG52
2622	AC-30P (1)	76.7	PG70
2622	AC-30P (2)	73.1	PG70

Table 19. Actual Temperature at Which the Value of G* sin δ Exceeds 5.0 MPA.

Contract	Binder	Temperature (^{0}C) at G* sin (d) = 5.0 MPA
N/A	AC-20	17.7
N/A	AC-20	21.2
2480	AC-20P	17.2
2491	AC-20P	19.0
2501	AC-30	22.7
2501	AC-20P	16.9
2530	AC-20P	15.9
2544	AC-20P	13.2
2545	AC-20P	19.5
2552	AC-20P	17.2
2558-93	AC-20P	20.4
2558-94	AC-20P	20.2
2591	AC-20P	22.4
2594	AC-20P	16.8
2603	AC-20+TLA	30.5
2604	AC-40	30.1
2604	AC-30	23.0
2611	AC-20	25.8
2611	AC-20P	15.9
2615	AC-20P	18.8
2617	AC-20P	18.5
2622	AC-30P (1)	23.4
2622	AC-30P (2)	23.3

Table 20. Potential of Binders to Experience Distress.

Binder	Rutting Potential	Fatigue Potential	Low Temperature Cracking Potential
2480	Potential for moderate rutting	Low fatigue potential	Very low
2491	Potential for low to moderate rutting	High fatigue potential	Very High
2501	Very low rutting potential	Low fatigue potential	Very Low
2501	Low rutting potential	Very low fatigue potential	Very low
2530	Low rutting moderate potential	Very low fatigue potential	Very low
2544	Very low rutting potential	Low fatigue potential	Low
2545	Low to moderate rutting potential	Moderate fatigue potential	Low
2552	High rutting potential	Very low fatigue potential	Very low
2558-93	Low rutting potential	Moderate fatigue potential	Low
2558-94	Moderate rutting potential	Moderate fatigue potential	High
2591	Very low rutting potential	Very high fatigue potential	Very high
2594	Low rutting potential	Very low fatigue potential	Very low
2603	Rut resistant	High fatigue potential	Low
2604-1	Very low rutting potential	High fatigue potential	Low
2604-2	Rut resistant	Low fatigue potential	Very low
2611-1	Rut resistant	Very high fatigue potential	Very high

Table 20. Potential of Binder to Experience Distress (cont'd).

Binder	Rutting Potential	Fatigue Potential	Low Temperature Cracking Potential
2615	Moderate to high rutting potential	Very high fatigue potential	High
2617	Very low rutting potential	Very low fatigue potential	Very low
2622-1	Rut resistant	Low fatigue potential	Very low
2622-2	Rut resistant	Low fatigue potential	Very low
2611-2	Rut resistant	Low fatigue potential	Low

Summary and Conclusion

The newly developed SHRP binder specification system was successfully used to grade twenty-three Nevada binders. All the rheological tests were conducted without any problems following the procedures recommended by SHRP.

The SHRP grading system clearly identified the AC-30, AC-20+TLA, and the AC-30P binders as having different rheological properties from the other binders. They were identified to be more desirable in warmer temperatures than the AC-20Ps, while their low temperature characteristics were less desirable than the AC-20Ps.

There were some discrepancies among the grading of the various AC-20P binders. The SHRP grading system indicated that some AC-20P binders would be appropriate over a wider temperature range than others. One of the AC-20P binders was identified as being applicable under a very narrow range of temperatures (2491). One disturbing observation is that the SHRP system graded an AC-20 as PG64-16 and another AC-20 as PG64-22 which indicates that both of these unmodified binders would perform better than the polymerized AC-20Ps. The system also graded an AC-40 (2604) as PG64-10, which is below the AC-30 and the AC-30P binders.

At this stage it is not known whether this discrepancy is coming from the SHRP grading system itself or if the AC-20P binders are actually different. The temperature susceptibility characteristics of the various binders indicate that the latter may be true.

The rheological data showed consistent behavior from all the binders that were classified under the same group. This indicates that the field performance of these binders should be very similar.

The environmental data needed for the recommendation of the specific binders were obtained from the Superpave model. In the majority of the cases, the Superpave recommendations did not coincide with the determined grades of the binders. The Superpave recommendations were too conservative on the high temperature grade.

It is highly recommended that the field performance of these projects be monitored and field samples be obtained to validate the applicability of the SHRP grading system for Nevada's conditions.

FHWA recommends that every state highway agency validate the SHRP binder and mixture testing and evaluation systems for its own conditions prior to the implementation process. The results of this research project and the follow-up study recommended in phase 2 would provide NDOT with the necessary data for the validation and implementation of SHRP systems.

NATIONAL CENTER FOR ASPHALT TECHNOLOGY EXPERIENCE

Data Base for the Southeastern United States

The National Center for Asphalt Technology (NCAT) was asked to develop a data base of the SHRP gradations for asphalts being used in the southeastern United States and to determine how those grades relate to viscosity grading systems. The results of this study are presented in a paper entitled ***SHRP Properties of Asphalt Cement***, prepared by Douglas I. Hanson, Rajib Bl. Mallick and Kee Foo of NCAT. The paper was presented at the 74th Annual Meeting of the Transportation Research Board in Washington, D.C., January, 1995.

The NCAT study consisted of forty-eight asphalts currently supplied to the southeastern states. No modified asphalts were included in the study. Twenty-three of the samples collected graded as AC-20, twenty-four as AC-30 and one as AC-10.

Table 21presents the viscosity and SHRP classification of each of the forty-eight asphalts tested. The AC-10 graded as a PG 58-22. On the upper temperature regime, nineteen of the AC-20s graded as a PG-64 and four graded as a PG-58. On the cold temperature regime sixteen of the AC-20s graded as PG-22, six graded as PG-16, and three graded as PG-28. On the upper temperature regime twenty-one of the AC-30s graded as a PG-64, one graded as a PG-58, one

Table 21. SHRP Asphalt Test Results.

Source of AC	AC Grade	Performance Grade
Texas	AC-20	PG 64-22
Texas	AC-20	PG 58-22
Texas	AC-20	PG 58-16
Texas	AC-20	PG 58-16
Virginia	AC-20	PG 64-22
Virginia	AC-20	PG 64-16
Virginia	AC-20	PG 64-22
Virginia	AC-20	PG 64-22
Virginia	AC-20	PG 58-16
Virginia	AC-30	PG 64-22
Virginia	AC-30	PG 64-22
Virginia	AC-30	PG 64-22
Virginia	AC-30	PG 64-22
Virginia	AC-30	PG 64-22
Virginia	AC-30	PG 64-16
South Carolina	AC-20S	PG 64-28
South Carolina	AC-30	PG 64-22
South Carolina	AC-20S	PG 64-22
Georgia	AC-20	PG 64-16
Georgia	AC-30	PG 64-22
Georgia	AC-30	PG 64-22
Georgia	AC-20	PG 64-16
Georgia	AC-30	PG 64-16
Georgia	AC-20	PG 64-28
Georgia	AC-30	PG 64-16
Georgia	AC-20	PG 64-22
Georgia	AC-30	PG 64-22
Georgia	AC-20	PG 64-28
Georgia	AC-20	PG 64-28

NOTE: all of the asphalt cements shown in this table are unmodified materials.

Table 21. SHRP Asphalt Test Results (cont.).

Source of AC	AC Grade	Performance Grade
Mississippi	AC-30	PG 64-22
Mississippi	AC-30	PG 64-22
Mississippi	AC-30	PG 64-28
Mississippi	AC-30	PG64-22
Arkansas	AC-20	PG 64-22
Arkansas	AC-30	PG 64-22
Arkansas	AC-30	PG 64-22
Arkansas	AC-30	PG 64-22
Louisiana	AC-30	PG64-22
Louisiana	AC-30	PG 64-16
Louisiana	AC-30	PG 64-34
Alabama	AC-20	PG 64-22
Alabama	AC-20	PG 64-22
Alabama	AC-20	PG 64-22
West Virginia	AC-20	PG 64-28
West Virginia	AC-20	PG 64-22
West Virginia	AC-10	PG 58-22
West Virginia	AC-20	PG 64-22
Florida	AC-30	PG 70-22
Florida	AC-30	PG 64-16
Florida	AC-30	PG 62-22

NOTE: all of the asphalt cements shown in this table are unmodified materials.

graded as a PG-70 and two graded as a PG-62. On the cold temperature regime seventeen of the AC-30s graded as a PG-22, six graded as a PG-16, one graded as a PG-28 and one graded as a PG-34. In summary, of the forty-seven AC-20 and AC-30 asphalt cements tested, twenty-eight graded as PG 64-22, eleven graded as PG 64-16, three graded as PG 58-16, five graded as PG 64-28, one graded as PG 64-34 and one graded as PG 70-22.

Results and Conclusions

Table 22 shows the average of properties determined from the testing for the AC-20 and AC-30 binders. Table 23 presents the requirements for each of the states in the region at the 90 percent reliability level based on the SUPERPAVE weather database. The asphalts tested in the NCAT study meet the SHRP requirements for an asphalt cement within the region approximately 50 percent of the time.

Table 22. SHRP Asphalt Data Averages.

Item	AC-20		AC-30	
	Mean	**Stan Dev**	**Mean**	**Stan Dev**
Vis @ 140	2051	207	3107	259
Vis @ 275	425	69	508	45
Pen @ 39.2	25	20	18	10
Pen @ 77.0	75	12	63	10
Pen Index	3.83	4.43	3.216	2.134
PVN	-0.48	0.28	-0.321	0.25
Duct 77	137	21	147	10
Soft. Pt.	120	2.3	123	5
Vis-TFO-140	5017	836	8294	2117
Vis-TFO-275	588	78	739	105
Pen-TFO-39.2	16.1	7.5	13	6.7
Pen-TFO-77	47.7	5.4	42.1	8.1
Pen Index	3.90	3.64	5.07	3.05
PVN	-0.285	0.273	0.020	0.401
Soft.Pt.	130	3.40	134.6	2.04
% Loss TFO	0.154	0.102	0.140	0.115
DSR-Original-64	1.136	0.124	1.715	0.172
DSR-Original-70	0.58	0.058	0.847	0.091
DSR-RTFO-64	2.870	0.935	4.537	1.190
DSR-RTFO-70	1.421	0.429	2.644	1.746
DSR-PAV-10	5.275	1.317	6.066	1.892
DSR-PAV-13	4.439	1.262	4.716	1.505
Flex Cr. - 18	335.5	97.3	345.0	129
m	0.276	0.023	0.263	0.023

Table 23. Asphalt Grades Suggested for use in Region 90 Percent Reliability Level.

STATE	SUGGESTED PG GRADE
Alabama	58-16,64-16,64-22,64-28
Arkansas	64-22,64-28,64-34,70-22
Florida	58-10,64-16
Georgia	58-28,64-16,64-22,64-28
Louisiana	58-10,64-10,64-16,64-22
Mississippi	64-16,6-22,64-28
North Carolina	52-34,58-28,58-22,58-16,64-16,64-22
South Carolina	58-16,64-16,64-28
Texas	58-10,58-22,64-10,64-16,64-22,64-28,64-34,70-16,70-22
Tennessee	58-28,58-34,64-22,64-28,64-34
Virginia	58-16,58-22,58-28,64-22,64-28
West Virginia	52-34,58-28,58-34,64-28,64-34

ZHANG AND HUBER STUDY

Background

The Heritage Research Group completed a study investigating the effect of the asphalt binder on pavement performance in July of 1995. In this study six different asphalt binders were included in typical Indiana densely graded mixes. The mixes were tested using SHRP mixtures tests and performance predictions were made based on the tests.

Asphalt Binders Selected and Evaluated

Table 24 presents the five asphalt binders selected in testing. These binders include an AC-20 typically used in Indiana, a gelled AC-10 (referred to as gel AC, a six percent polymer modified asphalt (PMAC(3%)), a six percent polymer modified asphalt (PMAC(5\6%)) and a performance grade PG 64-34 asphalt.

Table 24. Asphalt Binder Characteristics (after Zhang and Huber).

Test	Property	AC-20	Gel AC	PG 64-34	PMAC (3%)	PMAC (6%)	Specifications
Dynamic Shear, Original Binder, 12% strain, 64^0C,10 rad/s	G* (kPa)	1.15	3.44	1.09	1.12	2.13	(Tenderness) Min.: 1.0 kPa
	δ (degrees)	89.9	73.4	84.6	75.3	63.3	
	G*/sinδ (kPa)	1.15	2.54	1.10	1.16	2.38	
Dynamic Shear, KTPO 10% strain, 64^0C, 10rad/s	G* (kPa)	1.87	2.68	2.16	2.31	3.00	(Rutting) Min.: 2.2 kPa
	δ (degrees)	87.4	80.5	79.6	68.5	59.0	
	G*/sinδ, (kPa)	1.87*	2.72	2.30	2.48	3.5	
Dynamic Shear, PAV Residue, 1% strain, 22^0C, 10 rad/s	G* (kPa)	4114	2046	1209	2005	1980	(Fatigue Cracking) Max.: 5000 kPa
	δ (degrees)	49.0	51.7	42.8	49.5	49.3	
	G* sinδ (kPa)	3106	1605	820	1525	1500	
Creep Stiffness, PAV Residue, 60g	-18^0C	-18^0C	-18^0c	-24^0c	-18^0c	-18^0c	(Low Temperature Cracking) Max.: 5 = 300 MPa Min.: m= 0.30
	5 (MPA)	286.2	139.9	171.8	143.9	157	
	m-value	0.293**	0.331	0.323	0.366	0.353	
PG Grade		PG 58-22	PG 64-28	PG 64-34	PG 64-28	PG- 64-28	

* Fails to meet PG 64 but does meet PG 58
** Fails to meet -28 but does meet -22 grade

Asphalt Mixture Tests

The asphalt mixtures including these five binders were fabricated to meet the requirements of a densely graded Indiana surface mix with a target air void content of about six percent. SHRP level two mixture tests were performed. The results of the mixture testing are summarized in Table 25. This table includes the elastic and plastic model material properties used in the SHRP, Superpave performance prediction model. The last two columns of the table present the range of material properties determined reasonable by SHRP under contracts A-005 and A-003A.

Results and Conclusions

The study demonstrated that the slope of the relationship between complex compliance and frequency (m-value) of the frequency sweep mixture test performs most reliably as predictor of mixture performance. Unfortunately, the current Superpave performance models do not always predict realistic levels of performance or values of distress.

High m-values are associated with high levels of rutting, whereas lower values are associated with lower values of rutting. On the basis of the m-value, the AC-20 and AC-20 with fiber binders have much higher rutting sensitivity than do the other binders. This sensitivity to rutting is not apparent from the traditional viscosity binder tests, Table 26, but is apparent from the $G^*/\sin\delta$ values in Table 23. Which rank the AC-20 binder as the most rut susceptible based on DSR testing of the RTFO-aged binder. The correlation between $G^*/\sin\delta$ and the m-value is not particularly strong with an r-square of 0.70 but is reasonable and offers the potential to select binders that will resist permanent deformation and provide longer performance life.

Zhang and Huber felt that the current Superpave predictive models are not ready for use and need refinement and calibration. They did not assess the ability of the SHRP binder properties to assess fatigue cracking and low temperature cracking.

Table 25. Intermediate Materials Properties. (after Zhang and Huber).

Material	Property	AC-20	AC-20/ Fiber	Gel AC	PG-64-34	PMAC (3%)	PMAC (6%)	A-005	A-003A
Nonlinear	k_1	3670.5	3679.0	1887.5	1629.5	1396.5	1835.5	664-7199	728-3015
Elastic	k_2	0.193	0.378	0.374	0.421	0.386	0.393	0.17 - 0.89	0.18 - 0.46
	k_3	0	0	0	0	0	0	0	0
	k_4	0	0	0	0	0	0	0	0
	k_5	-0.355	-0.607	-0.414	-0.639	-0.415	-0.398	-0.301 - -2.66	-0.93 - - 2.36
	K_0(kPa)	96.5	420.6	167.5	159.2	151.0	144.1	68.95 - 148.9	68.95 - 212.4
Plastic		5.6	5.6	5.6	5.6	5.6	2.8	5.6-316	6.9-39.3
	(kPa)	524.0	551.6	151.7	530.9	156.5	170.3	275.8 - 675.7	110.3 - 779.1
	$_p$	25.3	29.3	22.3	26.3	22.3	22.3	26.6 - 60	20.4 - 33.5
	$_{cv}$ (degree)	20.5	22.5	20.2	22.5	21.2	11.6	22.5 - 59.1	0.25.0
Constant of Creep Compliance Equation	D_1	2.21 x 10^{-4}	1.11 x 10^{-4}	2.13 x 0^{-4}	2.25x 10^{-4}	2.69 x 0^{-4}	2.60 x 10^{-4}	-----	-----
Creep Compliance in Shear	m	0.4036	0.4538	0.3164	0.3386	0.2865	0.3024	-----	-----

Table 26. Physical Properties of Asphalt Binders. (after Zhang and Huber).

Property	AC-20	Gel AC	PG64-34	PMAC(3%)	PMAC(6%)
Rotational Viscosity, at 135^0C, Pas	0.331	2.000	0.345	0.600	1.450
Viscosity at 60^0C, P. At 1 sec $^{-1}$	2239	5600	2150	2543	15,200
Penetration at 25^0C, 100g, 5 sec. dmm	77	82	92	116	96

STATE EXPERIENCE WITH SUPERPAVE

Several state transportation departments as well as a few county and city agencies use the Superpave binder and mixture systems on a limited basis. A survey conducted by the Nevada T^2 Center revealed that some level of effort regarding implementation of Superpave is ongoing in at least 16 states. A summary of this survey which describes each state's experience with Superpave is presented in Table 27.

All 16 states shown in Table 27 have some degree of experience with the Superpave binder selection system; however, most of these states are still in the stage of evaluating the equipment and specifications. Projects incorporating the performance grade binders have been built on an experimental basis and full implementation of the PG binder specification is scheduled in the near future.

A few states use the Superpave mixture design system on an experimental basis and report positive results thus far regarding performance. Most projects were constructed in 1995; therefore, it is too early to adequately assess pavement performance.

Where reported, Superpave mixtures cost more than previously used conventional mixtures; however, some contacts anticipate that prices will drop as familiarity with materials expands.

In general, the personnel contacted in this survey were very positive in their expectations of the Superpave System. Longer pavement life and less maintenance costs are anticipated by most states included in this survey.

Table 27. Summary of Case Histories on the Use of Superpave Binder and Mix Systems.

State	Experience with SUPERPAVE	Performance	Expectations	Cost
Alabama	Superpave mix was placed on a 5-mile resurfacing project of State Route 165 in 1995 in cooperation with NCHRP research project 9-7. Binder met the PG 76-22 criteria (AC-30 with 8 percent crumb rubber). Mixture designs were developed for 25 mm and 37.5 mm maximum size aggregates.	Problems of segregation were anticipated in the 37.5 mm mix and were minimized to a great extent. The 25 mm mix produced a more aesthetically-pleasing riding surface and proved to be more manageable during both production and placement. The use of an Alabama DOT specification designed to incorporate the Superpave aggregate, binder and mix design requirements created no major problems for the DOT or the contractor.	Laboratory-conducted tertiary creep tests indicate that the pavement overlay should be extremely resistant to rutting. The expected rutting resistance will result in an improved pavement surface profile thus reducing potential for wet-weather accidents. Full implementation of the Superpave program is scheduled for 2000. However, implementation for the binder testing and specifications is scheduled for 1997. Level I mix design is scheduled for trial projects in 1997.	The bid price for the Superpave mix was less than 15 percent higher than the price bid for the planned conventional mix.
Alaska	Superpave binder selection system was used on two projects.	Performance expectations have been met in that no thermal cracks have been observed.	Pavement life (typically 10 years) is dictated by depth of rutting due to studded tires. If studded tires were not a factor, longer pavement life would be anticipated. Reduction in maintenance costs are anticipated due to less thermal cracking resulting from the Superpave binder selection system. Full implementation of Superpave scheduled for 1997.	Costs on two projects reflect a first capital cost of 50 percent higher which was associated with equipment needs (bigger circulating pumps to pump modified binders) and materials costs (addition of polymers). However, it is believed the binders will be cost-effective due to decreased maintenance. Higher mixture costs are anticipated in order to achieve VMA, crushed fines, and higher voids in total mix. The higher mixture costs expected will be offset by lower anticipated binder contents.
Colorado	City of Fort Collins is planning a Superpave project for a high-traffic intersection (40,000 ADT, 6% trucks). The pavement design calls for a 6-inch full depth plant-mix base course and 3-inch surface course using 3/4-inch aggregate.	Not available.	Several road agencies in Colorado are considering Superpave specifications including the Colorado DOT, City of Aurora and City of Fort Collins.	The Superpave mix will be about $3 more per ton than a conventional mix. The city is also considering the use of polymer additives which would increase the cost to about $14 more per ton than a conventional mix.

Table 27. Summary of Case Histories on the Use of Superpave Binder and Mix Systems (con't).

State	Experience with SUPERPAVE	Performance	Expectations	Cost
Kentucky	Superpave PG 70-22 binder and 9.5 mm nominal size mix was used on the East-West Connector in the Frankfort area in 1995. One and one-half inches of the original material was milled and replaced on this four-lane facility for a distance of five miles.	Not available.	Three projects contracted for 1995. Performance Grade asphalt will be permitted as an option to all AC grades in 1996. Full implementation of Superpave binder specs will occur in 1997. Full use of Superpave binder and mix design specifications is scheduled for 2000. It is expected that with Superpave, the life of Kentucky pavements on the heavy volume routes will increase. Construction time will not change appreciably.	Upon implementation of the Performance Grade specification, expected binder costs may increase about 10%, but this is primarily due to the new specification testing. It is expected that costs well level out to about the same as in the past. The costs for pavement maintenance and rehabilitation should be greatly reduced. The savings should be substantial if the 3-year repaving cycle can even be increased to 6 years.
Michigan	Binder equipment has been used to evaluate asphalt cements currently certified for use on MDOT projects. An examination of the effects of different RAP percentages on performance grades was initiated using the binder equipment. A special provision that will use a PG grade binder will be introduced on some projects during the 1995 construction season. Gyratory compactor is being evaluated. About 10 designs have been tested so far. SPS-9 section planned for 1995.	Not available.	Full Superpave mix design implementation scheduled for 2000. Gyratory compactor will be used on all mix designs tested this season to build up a data base and to gain more experience. Th gyratory compactor will provide valuable mix design information.	Not available.

Table 27. Summary of Case Histories on the Use of Superpave Binder and Mix Systems (con't).

State	Experience with SUPERPAVE	Performance	Expectations	Cost
Minnesota	Blue Earth County built a Superpave Level I design as an overlay to a low-volume pavement. The project consisted of a 2-inch overlay, 3.5 miles long on a county road. There were three test sections: 1. Control conventional mix. 2. Superpave mix using 120-150 pen asphalt. 3. Superpave mix using 200-300 pen asphalt.	Because the project is so recent, any judgment as to performance is limited to an intuitive feeling that "it was a good-looking materials going down."	Expected benefits to be realized include longer pavement life and decreased maintenance costs.	The Superpave mix was slightly more expensive than conventional (less than 5 percent).
Missouri	Asphalt binder equipment products are being used in the Central Materials Laboratory of the Materials and Research Division. The binder equipment is used in day-to-day testing of asphalt to verify SHRP binder grade. Superpave binder testing requires more time than conventional asphalt testing. A level I Superpave mix project is in the design process for an SPS-9a experiment.	Not available.	Long -term cost savings, less pavement rutting, and longer pavement life are anticipated with the implementation of the Superpave binder specification (full implementation planned for 1997). There is concern regarding the reliability and durability when full transition to Superpave binder specifications occur. There is also concern that sample throughput will be inadequate.	On the test projects using the performance grade binder, the asphalt cement cost was double previous costs. The HMA cost increased approximately $7.00 per ton.
Nebraska	The gyratory compactor was used during the first half of 1995 to help the City of Lincoln develop a mix design for a Superpave Level I experimental project.	The compactor produced very satisfactory specimens and does a good job of replacing the Marshall compactor.	Laboratory compacted samples will more closely simulate field compaction of asphalt pavements.	Not available.

Table 27. Summary of Case Histories on the Use of Superpave Binder and Mix Systems (con't).

State	Experience with SUPERPAVE	Performance	Expectations	Cost
New Mexico	Equipment acquisition is underway. All equipment is in place needed to implement Superpave Level I mix designs. Superpave aggregate grading specifications have been used on 2 projects. FHWA-loaned binder equipment was utilized in-state for a 6-week period to gain some hands-on experience. An SPS-9 pavement section is planned on I-10 near Lordsburg.	Not available.	For 1996, it is expected that each district will build at least one project using the Superpave gradation controls.	Not available.
New York	The DOT built five pilot projects during 1995 using asphalt binders meeting Superpave specifications. All projects were located in the Adirondack Mountains and were selected due to the area's history of low-temperature cracking. The projects ranged from full-depth reconstructions to recycled partial-depth reconstructions to simple overlays. Fifty-six miles of roadway were paved. Comparisons will be made to sections built with conventional AC-20.	Not available.	Although the full benefits of the Superpave system will not be realized until the mix test equipment is in-place and operational, information gathered from the pilot projects will be a valuable first step in understanding this technology. New York State DOT plans on building more test sections incorporating both Superpave binder and mix design technologies.	The mix containing the performance grade binder increased the cost of the asphalt by about $11 per metric ton; however, the DOT expects the price to drop significantly as familiarity of the materials increases and the market expands.

Table 27. Summary of Case Histories on the Use of Superpave Binder and Mix Systems (con't).

State	Experience with SUPERPAVE	Performance	Expectations	Cost
North Carolina	All binder and mix equipment is in place. Eight test sections are planned for SPS-9 study: *New construction* 1. NC standard binder and mix. 2. Superpave Baseline PG-binder and Superpave mix. 3. Superpave Alternative PG-binder and Superpave mix. *Overlay* 4. NC standard binder and mix. 5. Superpave Baseline PG-binder and Superpave mix. 6. SBR Polymer modified binder and Superpave mix. 7. SBS Polymer modified binder and Superpave mix. 8. Polymer modified binder and SMA.	Not available.	NCDOT has invested its time and money into these products for the potential of increasing pavement performance. Simply, if the pavements last longer, less money will be used to maintain them. Increased pavement performance and the cost savings associated with using this technology are the perceived benefits from the use of these SHRP products.	Not available.
North Dakota	North Dakota began using the asphalt binder equipment in 1995. The equipment is used in the North Dakota Materials and Research Lab to grade asphalt binders. North Dakota is still in the process of evaluating the equipment, but preliminary comments and test results are positive.	Not available.	Thermal cracking is a problem that North Dakota is trying to combat and it expects that the use of appropriate binders will extend pavement life and minimize cracking. North Dakota is planning to convert its penetration graded specifications to a performance graded system. Overall, North Dakota is optimistic about the equipment potential, information, and test data that can be obtained from using this SHRP product.	

Table 27. Summary of Case Histories on the Use of Superpave Binder and Mix Systems (cont'd).

State	Experience with SUPERPAVE	Performance	Expectations	Cost
Pennsylvania	Two projects have been built using Superpave asphalt binder specifications: One project was a one-mile long climbing lane added to US Route 22, the other was the rehabilitation of two intersections near Allentown. Both projects were constructed in 1995. PennDOT used a Superpave Level I mix design for the US Route 22 pavement. The intersection pavement was constructed by the City of Allentown.	Not available.	PennDOT anticipates about 6 new projects for 1996 using the PG binder specifications.	Not available.
Tennessee	Level I mix design placed on State Route 109 in 1994 using PG70-28. This is an area of heavy and slow truck traffic going between the numerous truck stops and the interstate. Design based on 15.2 million ESAL. Surface thickness was 1.5 inches and binder course was 3-inches thick.	After 3 months of service, performance is good. Mix designs proved to be coarser and contained lower asphalt content than conventional surface and binder mixes. Local aggregates did not always provide the necessary fine aggregate angularity and gradations needed for the target VMAs.	Work is underway to develop a surface and binder Level I mix design for a heavily rutted intersection near Nashville.	Not available.
Texas	Superpave binder testing equipment is in place (except for direct tension) and focus has been on evaluating the binder specification and supporting tests. .	Not available.	Binder specification implementation scheduled for 1997. Evaluations of Superpave mixture tests are being deferred until equipment is available and the regional Superpave Centers conduct some evaluation	A gross estimate of savings to be realized by implementation of the Superpave binder specification is placed at $2.2 billion over 30 years.

Table 27. Summary of Case Histories on the Use of Superpave Binder and Mix Systems. (Cont'd).

State	Experience with SUPERPAVE	Performance	Expectations	Cost
Washington	WSDOT has written a provisional specification to implement the PG specifications for 3 test sections during the 1995 construction season. Each of the 3 jobs will require about 20,000 tons of hot mix . The state reviewed and evaluated the climatic regions of Washington to categorize the appropriate grade per region. Western Washington is all one grade: 58-22. Northeastern Washington is 53-34 and southeastern areas are 64-28.	Not available.	Full implementation of Superpave binder specification is scheduled for 1997.	Not available.
Wisconsin	Three test sections placed on I-43 in 1992: 1. Superpave mix, 2. SMA mix, 3. Superpave Mix	After 2 years of service, rutting performance was as follows: Superpave mix 0.02 inch, SMA mix 0.05 inch, Conventional mix 0.02 inch. Reflective cracking results: Superpave mix 20 percent, SMA mix 35 percent, Conventional mix 55 percent.	Superpave performance models predicted the following at 2 years of service: Rutting < 0.1 inch, Cracking 20 percent.	Superpave mix cost was 25 percent more than conventional mix. SMA mix cost was 15 to 35 percent more than conventional.

Cost Savings of Improved Binder Specifications

Many asphalt overlays use the incorrect binder specification for the given load and climate conditions. The Texas case study estimated that approximately 25 percent of overlays use the wrong binder. As a result of the SHRP research, improved asphalt binder specifications have been developed. These improved binder specifications allow those pavements which have had overlays using inferior binders to last longer between overlays. By properly specifying the correct binder for overlays, pavement and overlay life can be extended. The Texas case study estimates that time between overlays can be extended from 8 years, using the wrong binder, to 12 years, using the correct binder. For purposes of the cost savings estimates in this section, a more conservative increase to 10 years is used to take into account potentially less variability in the use of incorrect binders in other states.

In order to estimate the potential savings of the improved binder specifications, it is first necessary to estimate the number of highway miles that could be impacted. Tables 28 and 29 give the total highway mileage in the United States for urban and rural areas, respectively. Over half of the total mileage is in the rural collector categories. The mileage in the local functional class is excluded from these totals because they primarily consist of low-volume roads with either no pavement or a thin surface treatment. There would be few highway sections in the local functional class that would benefit by improved binder specifications.

Table 30 gives the breakdown of vehicle miles traveled by functional class and highway type. The vehicle miles traveled are necessary to estimate the average daily traffic for each highway type to be used in the MicroBENCOST computer program. It is interesting to note that only a small portion of the vehicle miles traveled are on the rural collector classes, which make up the bulk of highway mileage. Most vehicle miles are concentrated on the higher functional classes in urban areas.

Tables 31 and 32 give the total asphalt highway mileage in the United States, along with a breakdown by highway type. *Highway Statistics* (1) does not give highway mileage cross classified by type of surface and highway type. Therefore the proportion of total mileage for each functional class is used to categorize the asphalt pavement mileage by highway type. Nearly all the asphalt highway mileage is concentrated in the 2-lane undivided category. Asphalt highway mileage covers several categories of pavement type surface categories, including intermediate, high flexible and high composite. The low pavement type was excluded because it consists of a pavement surface thickness of 1 inch or less. The improved binder specifications would not be applicable in most cases to these thin surface treatments.

Tables 33 and 34 give vehicle miles traveled by highway type. Again, *Highway Statistics* (1) does not give a breakdown of vehicle miles traveled by highway type, so the proportion of each highway type to the total for each functional class is used to make those estimates. The freeway and 2-lane undivided highway categories have the highest totals of vehicle miles traveled, with a smaller total for the 4-lane divided category.

Table 35 is a summary table giving the average daily traffic volumes and highway mileage by highway type. Not surprisingly, the urban freeways have the highest traffic and the rural undivided highways have the most mileage. The average daily traffic volumes are used in the MicroBENCOST program to estimate agency and motorist savings for each of the six highway type categories. The MicroBENCOST analysis makes estimates for a one-mile highway segment by comparing the costs of continuing to use current binder specifications over a 40 year life cycle versus using the improved binder specifications. The asphalt mileage with the wrong binder is used to aggregate the MicroBENCOST results for potential cost savings nationwide. The analysis uses 25 percent as the amount of asphalt mileage in the U.S. with the wrong binder, the amount estimated in the Texas case study.

One of the main benefits to transportation agencies of improved binder specifications is reduction in the frequency of overlays for those highways using the wrong binder for overlays. In order to estimate the savings of fewer overlays, it is necessary to have information on the costs of overlays. Federal Highway Administration has made estimates of average overlay costs as part of their Highway Performance Monitoring System (HPMS) (2). These estimates are given in Table 36, which represents an average of the more detailed HPMS numbers. The Texas case study uses $60,000 per lane mile with current binders, and a higher $64,000 per lane mile using improved binders. This amounts to an increased cost of 6.67 percent, which is used in Table 35 for the improved binder costs. The Texas case study does not give a breakdown of overlay costs by highway type, but the $60,000 per lane mile would be equivalent to $240,000 per mile for 4-lane highways and $120,000 per mile for 2-lane highways. These numbers are roughly comparable to the numbers in Table 36, with some higher and others lower, as would be expected. It is concluded that the numbers in Table 36 are reasonable and can be used to estimate cost savings nationwide.

The main benefits to motorists of improved binders is the reduction in delay and vehicle operating costs caused by rough pavements. Rough pavements cause vehicles to slow down and cause increased fuel consumption and wear on the vehicle. Improved asphalt binders would allow motorists to travel on smoother pavements for longer periods of time before the roadways deteriorate and require an overlay. MicroBENCOST uses the Present Serviceability Index (PSI) to estimate the motorist impacts of rough pavements. Table 37 gives the PSI values from HPMS (2) for the PSI immediately after an overlay and the minimum PSI triggering an overlay. MicroBENCOST requires a PSI value for each year over the analysis period, so the values in Table 37 are used to estimate the coefficients of an equation, which in turn is used to estimate PSI values for each year. The equation is in the form:

$$PSI_t = PSI_o - bt^c$$

where,

PSI_t = calculated PSI for year t,

PSI_o = PSI in first year of overlay,

t = year t,

b,c = calculated coefficients.

Table 38 gives the calculated PSI values for each highway type over a 40 year analysis period. A 40 year analysis period was chosen because both the 8-year cycle and 10-year cycle end together at 40 years. The current binder has five 8-year cycles and the improved binder has four 10-year cycles. In addition, a long analysis period minimizes any distortions in the life-cycle costs using shorter periods. While there is no perfect way to compare alternatives with different lives, the forty year analysis period in this instance will give a good approximation of the relative savings that can be expected using improved asphalt binders.

The ADT values in Table 35, the overlay costs in Table 36, and the PSI values in Table 39, were used to make several runs using the MicroBENCOST PC computer program. A 40 year analysis period was used, along with a 5 percent discount rate. In addition, an annual traffic growth rate of 2.1 percent was assumed, which is approximately the historical growth of traffic in the United States (3).

The results of the analysis for each highway type are given in Table 39. Detailed MicroBENCOST outputs are given in Appendix D. The agency cost savings consist of overlay cost savings partially offset by some implementation costs. These implementation costs are derived from the Texas case study information and consist of new binder test equipment, annual maintenance on the equipment and additional personnel costs to conduct the tests. The motorist cost savings are broken down into two categories, delay savings and reduction in vehicle operating costs (VOC). As expected the greatest savings are for the higher volume facilities and much lower savings for the low-volume highways. The urban freeway, for example, would generate more than a million dollars per mile in motorist savings and over $200,000 per mile in agency savings. In contrast the rural 2-lane highway would result in about $51,000 in motorist savings and $35,000 in agency savings.

In order to compare the cost savings, it is necessary to convert the total savings per mile in Table 38 to an annual cost savings. This can be done using equivalent uniform annual cost factors. The factor for a uniform series over 40 years using a 5 percent discount rate is 17.16. By dividing each number in Table 39 by 17.16, it can be converted into annual savings. These annual numbers are given in Table 40. The numbers range from $72,184 for an urban freeway to $5,004 for a rural 2-lane undivided highway.

These annual cost savings per mile can then be aggregated using the total asphalt mileage with the wrong binder, as shown in in Table 34. The total annual cost savings are given in Table 41. This table shows that a total of almost $2.8 billion could be saved annually in the U.S. using improved binders for asphalt overlays. Of this total, about $750 million would represent annual agency savings, and $2 billion represents annual motorist savings.

The numbers in Table 39 represent the total potential annual savings if all agencies immediately implemented the improved binder specification. Of course there is an implementation process that will be followed as states experiment with improved binders and gradually increase the use of the binders as favorable results are demonstrated. That implementation will occur over the next few years and is expected to vary widely from state to state. For those reasons the total shown in Table 41 may not give a realistic picture of the practical benefits that can be expected from improved binder specifications.

Tables 42, 43, and 44 give estimates of the total estimated benefits over 20 years assuming a "slow" implementation scenario, a "moderate" implementation scenario, and a "fast" implementation scenario, respectively. The slow implementation scenario assumes a 100 percent implementation after 10 years, the moderate implementation scenario assumes a 100 percent implementation after 5 years, and the fast implementation scenario assumes a 100 percent implementation occurring immediately. There is an indication that several states will be using the new binder specifications in the near future because of the substantial savings that can be generated by switching to the improved binders. Therefore, these scenarios give a reasonable range on the potential benefits of likely implementation scenarios. The potential cost savings are substantial, ranging from $22.5 billion to $36.5 billion over the next twenty years. The savings to agencies alone would range from $6.0 to $9.8 billion in present value dollars.

Table 28.   Urban Highway Mileage in United States by Functional Class and Highway Type[1]

Highway Type	Urban Functional Class					
	Inter-state	Other Freeway	Other Prin Art	Minor Arterial	Collect	Total
Freeway	13,126	7,171	3,754	1,089	74	25,214
4-Lane Divided	0	1,106	28,362	23,334	6,650	59,452
2-Lane Undivided	0	718	20,974	63,429	79,374	164,495
Total	13,126	8,995	53,090	87,852	86,098	249,161

[1] Excludes highway mileage in local functional class. Local functional class is defined as "local roads and streets, which serve the land access function to the residential areas, individual farms, and other local areas." Freeway is defined as 4-lane divided highway with full or partial access control. 4-Lane Divided is defined as 4-lane divided with no access control and other.

Source: *Highway Statistics*, 1994 (1), Table HM-55, pp. V44-V45.

Table 29. Rural Highway Mileage in United States by Functional Class and Highway Type[1]

Highway Type	Rural Functional Class					
	Inter-state	Other Prin Art	Minor Arterial	Major Collect	Minor Collect	Total
Freeway	32,457	9,846	906	554	0	43,763
4-Lane Divided	0	14,725	5,753	4,215	0	24,693
2-Lane Undivided	0	72,424	131,512	426,342	282,025	912,303
Total	32,457	96,995	138,171	431,111	282,025	980,759

[1] Excludes highway mileage in local functional class. Freeway is defined as 4-lane divided highway with full or partial access control. 4-Lane Divided is defined as 4-lane divided with no access control and other. Rural Minor Collector not broken down by highway type, so all mileage is assigned to the 2-lane undivided category.

Source: *Highway Statistics*, 1994 (1), Table HM-57, pp. V46-V47.

Table 30. Annual Vehicle-Miles of Travel and Average Daily Traffic Volume by Functional Class

Functional Class	Annual Vehicle Miles Traveled (Millions)	Average Daily Traffic Volume
Urban		
Interstate	331,200	69,130
Other Freeway	147,560	44,944
Other Principal Arterial	364,492	18,810
Minor Arterial	286,359	8,930
Collector	120,118	3,822
Total	1,249,729	13,742
Rural		
Interstate	215,918	18,226
Other Principal Arterial	207,567	5,863
Minor Arterial	149,949	2,973
Major Collector	182,328	1,159
Minor Collector	48,561	472
Total	804,323	2,247

Source: VMT taken from *Highway Statistics* 1994 (1), Table VM-2, p. V-116. ADT calculated from VMT and highway mileage in Tables 28 and 29.

Table 31. Urban Asphalt Highway Mileage by Functional Class and Highway Type

	Urban Functional Class					
	Inter-state	Other Freeway	Other Prin Art	Minor Arterial	Collect	Total
Total Asphalt Mileage in U.S.[1]	7,845	5,749	46,862	79,290	76,765	216,511
Proportion of Total Mileage	0.60	0.64	0.88	0.90	0.89	0.87
Asphalt Mileage by Highway Type						
Freeway	7,845	4,583	3,314	983	66	16,791
4-Ln Div	0	707	25,035	21,060	5,929	52,731
2-Lane	0	459	18,514	57,247	70,770	146,990
Total	7,845	5,749	46,862	79,290	76,765	216,511

[1] Asphalt Mileage includes the following pavement type surface categories: Intermediate Type, High Type Flexible, High Type Composite.

Source: Asphalt mileage taken from *Highway Statistics* 1994 (1), Table HM-51, pp. V36-V37. Proportion of mileage calculated from asphalt mileage and total urban mileage, Table 28. Asphalt mileage by highway type calculated from proportion of total and mileage by highway type, Table 28.

Table 32. Rural Asphalt Highway Mileage by Functional Class and Highway Type

	Rural Functional Class					
	Inter-state	Other Prin Art	Minor Arterial	Major Collect	Minor Collect	Total
Total Asphalt Mileage in U.S.[1]	22,010	86,218	131,696	325,086	148,763	713,773
Proportion of Total Mileage	0.68	0.89	0.95	0.75	0.53	0.73
Asphalt Mileage by Highway Type						
Freeway	22,010	8,752	864	418	0	32,043
4-Ln Div	0	13,089	5,483	3,178	0	21,751
2-Lane	0	64,377	125,349	321,490	148,763	659,979
Total	22,010	86,218	131,696	325,086	148,763	713,773

[1] Asphalt Mileage includes the following pavement type surface categories: Intermediate Type, High Type Flexible, High Type Composite.

Source: Asphalt mileage taken from *Highway Statistics* 1994 (1), Table HM-51, pp. V34-V35. Proportion of mileage calculated from asphalt mileage and total urban mileage, Table 30. Asphalt mileage by highway type calculated from proportion of total and mileage by highway type, Table 31.

Table 33. Urban Vehicle Miles Traveled on Asphalt Highways by Functional Class and Highway Type

	Urban Functional Class					
	Inter-state	Other Freeway	Other Prin Art	Minor Arterial	Collect	Total
Prop. of Mileage by Highway Type						
Freeway	1.00	0.80	0.07	0.01	0.00	0.10
4-Ln Div	0.00	0.12	0.53	0.27	0.08	0.24
2-Lane	0.00	0.08	0.40	0.72	0.92	0.66
VMT (million) by Highway Type						
Freeway	331,200	117,638	25,773	3,550	103	478,266
4-Ln Div	0	18,144	194,721	76,059	9,278	298,200
2-Lane	0	11,779	143,998	206,751	110,737	473,266
Total	331,200	147,560	364,492	286,359	120,118	1,249,729

Source: Calculated from Tables 28 and 30.

Table 34. Rural Vehicle Miles Traveled on Asphalt Highways by Functional Class and Highway Type

	Rural Functional Class					
	Inter-state	Other Prin Art	Minor Arterial	Major Collect	Minor Collect	Total
Prop. of Mileage by Highway Type						
Freeway	1.00	0.10	0.01	0.00	0.00	0.04
4-Ln Div	0.00	0.15	0.04	0.01	0.00	0.03
2-Lane	0.00	0.75	0.95	0.99	1.00	0.93
VMT (million) by Highway Type						
Freeway	215,918	21,070	983	234	0	238,206
4-Ln Div	0	31,511	6,243	1,783	0	39,537
2-Lane	0	154,986	142,722	180,311	48,561	526,580
Total	215,918	207,567	149,949	182,328	48,561	804,323

Source: Calculated from Tables 29 and 31.

Table 35. Average Daily Traffic and Mileage by Highway Type.

Highway Type	Average Daily Traffic	Mileage by Category		
		Total Mileage	Asphalt Highway Mileage	Asphalt Mileage with Wrong Binder[1]
Urban				
Freeway	51,968	25,214	16,791	4,198
4-Lane Divided	13,742	59,452	52,731	13,183
2-Lane Undivided	7,882	164,495	146,990	36,747
Rural				
Freeway	14,913	43,763	32,043	8,011
4-Lane Divided	4,387	24,693	21,751	5,438
2-Lane Undivided	1,581	912,303	659,979	164,995

[1] Assumes 25% of Asphalt Highway Mileage use wrong binder specification.

Source: Calculated from Tables 28 through 34.

Table 36. Overlay Costs per Mile (Thousand $).

Highway Type	Urban		Rural	
	Current Binder	Improved Binder[1]	Current Binder	Improved Binder[1]
Freeway	608	649	325	347
4-Lane Divided	416	444	261	278
2-Lane Undivided	237	253	103	110

[1] Assumes the overlay costs with the improved binder specification increases 6.67%.

Source: Overlay costs using current binders taken from HPMS Technical Manual (2), pp. II-10 and II-13.

Table 37. Overlay and Minimum Present Serviceability Index Values by Highway Type.

Highway Type	Urban		Rural	
	PSI After Overlay	Minimum PSI	PSI After Overlay	Minimum PSI
Freeway	4.3	3.0	4.3	3.0
4-Lane Divided	4.2	2.8	4.2	2.8
2-Lane Undivided	4.0	2.4	4.0	2.4

Source: HPMS Technical Manual (2), pp. II-8, II-12, and II-16.

Table 38. Yearly PSI Values Used in MicroBENCOST.

Year	Freeway		4-Lane Divided		2-Lane Undivided	
	Current Binder	Improved Binder	Current Binder	Improved Binder	Current Binder	Improved Binder
1	4.30	4.30	4.20	4.20	4.00	4.00
2	4.29	4.30	4.19	4.20	3.99	4.00
3	4.24	4.29	4.13	4.19	3.92	3.99
4	4.13	4.26	4.02	4.15	3.79	3.95
5	3.96	4.20	3.84	4.09	3.58	3.87
6	3.72	4.09	3.58	3.97	3.29	3.74
7	3.40	3.93	3.23	3.80	2.90	3.55
8	3.00	3.70	2.80	3.56	2.40	3.27
9	4.30	3.40	4.20	3.23	4.00	2.89
10	4.29	3.00	4.19	2.80	3.99	2.40
11	4.24	4.30	4.13	4.20	3.92	4.00
12	4.13	4.30	4.02	4.20	3.79	4.00
13	3.96	4.29	3.84	4.19	3.58	3.99
14	3.72	4.26	3.58	4.15	3.29	3.95
15	3.40	4.20	3.23	4.09	2.90	3.87
16	3.00	4.09	2.80	3.97	2.40	3.74
17	4.30	3.93	4.20	3.80	4.00	3.55
18	4.29	3.70	4.19	3.56	3.99	3.27
19	4.24	3.40	4.13	3.23	3.92	2.89
20	4.13	3.00	4.02	2.80	3.79	2.40
21	3.96	4.30	3.84	4.20	3.58	4.00
22	3.72	4.30	3.58	4.20	3.29	4.00
23	3.40	4.29	3.23	4.19	2.90	3.99
24	3.00	4.26	2.80	4.15	2.40	3.95
25	4.30	4.20	4.20	4.09	4.00	3.87
26	4.29	4.09	4.19	3.97	3.99	3.74
27	4.24	3.93	4.13	3.80	3.92	3.55
28	4.13	3.70	4.02	3.56	3.79	3.27
29	3.96	3.40	3.84	3.23	3.58	2.89
30	3.72	3.00	3.58	2.80	3.29	2.40
31	3.40	4.30	3.23	4.20	2.90	4.00
32	3.00	4.30	2.80	4.20	2.40	4.00
33	4.30	4.29	4.20	4.19	4.00	3.99
34	4.29	4.26	4.19	4.15	3.99	3.95
35	4.24	4.20	4.13	4.09	3.92	3.87
36	4.13	4.09	4.02	3.97	3.79	3.74
37	3.96	3.93	3.84	3.80	3.58	3.55
38	3.72	3.70	3.58	3.56	3.29	3.27
39	3.40	3.40	3.23	3.23	2.90	2.89
40	3.00	3.00	2.80	2.80	2.40	2.40

Table 39. Discounted Cost Savings per Mile over a 40 Year Analysis Period (Thousand $)

	Urban			Rural		
	Freeway	4-Lane Divided	2-Lane Undivided	Freeway	4-Lane Divided	2-Lane Undivided
Agency Cost Savings						
Overlays						
Implement	207.00	142.00	81.00	111.00	90.00	35.00
Total	-0.17	-0.17	-0.17	-0.17	-0.17	-0.17
	206.83	141.83	80.83	110.83	89.83	34.83
Motorist Cost Savings						
Delay	234.43	179.99	135.22	61.79	57.89	17.38
VOC	797.36	458.43	137.02	275.71	160.70	33.65
Total	1,031.79	638.42	272.24	337.50	218.59	51.03
Total Cost Savings	1,238.62	780.25	353.07	448.33	308.42	85.86

Source: Output from MicroBENCOST program.

Table 40. Equivalent Uniform Annual Cost Savings per Mile ($).

	Urban			Rural		
	Freeway	4-Lane Divided	2-Lane Undiv	Freeway	4-Lane Divided	2-Lane Undiv
Agency Cost Savings						
Total	12,053	8,265	4,710	6,459	5,235	2,030
Motorist Cost Savings						
Delay	13,662	10,489	7,880	3,601	3,374	1,013
VOC	46,469	26,716	7,985	16,068	9,365	1,961
Total	60,131	37,206	15,866	19,669	12,739	2,974
Total Cost Savings	72,184	45,471	20,576	26,128	17,974	5,004

Table 41. Total Annual Cost Savings (Million $)

	Urban			Rural			Total
	Frwy	4-Ln Div	2-Ln Undivided	Frwy	4-Ln Div	2-Ln Undivided	
Agency Cost Savings Total	50.60	108.96	173.09	51.74	28.47	334.87	747.73
Motorist Cost Savings							
Delay	57.35	138.28	289.58	28.85	18.35	167.12	699.53
VOC	195.08	352.20	293.43	128.72	50.93	323.57	1,343.93
Total	252.43	490.49	583.01	157.57	69.27	490.68	2,043.46
Total Cost Savings	303.03	599.45	756.11	209.31	97.74	825.55	2,791.19

Source: Calculated from Table 40, using wrong binder mileage Table 35.

Table 42. Total Cost Savings with a Slow Implementation Scenario.

Year	Implementation Rate (Percent)	Discounted Agency Savings (Million $)	Discounted Motorist Savings (Million $)	Total Discounted Savings (Million $)
1	2.4	17.95	49.04	66.99
2	6.8	48.42	132.34	180.76
3	13.3	90.20	246.51	336.71
4	21.4	138.23	377.76	515.98
5	31.0	190.70	521.16	711.86
6	42.2	247.24	675.66	922.90
7	54.7	305.21	834.10	1,139.31
8	68.6	364.54	996.24	1,360.78
9	83.7	423.60	1,157.65	1,581.25
10	100.0	481.99	1,317.23	1,799.22
11	100.0	459.04	1,254.51	1,713.55
12	100.0	437.18	1,194.77	1,631.95
13	100.0	416.37	1,137.87	1,554.24
14	100.0	396.54	1,083.69	1,480.23
15	100.0	377.66	1,032.08	1,409.74
16	100.0	359.67	982.94	1,342.61
17	100.0	342.54	936.13	1,278.68
18	100.0	326.23	891.55	1,217.79
19	100.0	310.70	849.10	1,159.80
20	100.0	295.90	808.67	1,104.57
20-Year Total		6,029.91	16,478.99	22,508.91
Equiv. Ann. Tot.		483.86	1,322.32	1,806.17

Source: Calculated from Table 40, using a 5 percent discount rate. Equivalent annual totals are calculated using a factor of 12.4622, to convert the 20 year totals into annual values.

Table 43. Total Cost Savings with a Moderate Implementation Scenario.

Year	Implementation Rate (Percent)	Discounted Agency Savings (Million $)	Discounted Motorist Savings (Million $)	Total Discounted Savings (Million $)
1	6.8	50.85	138.96	189.80
2	21.4	152.39	416.48	568.87
3	42.2	286.21	782.17	1,068.37
4	68.6	443.10	1,210.94	1,654.04
5	100.0	615.16	1,681.16	2,296.32
6	100.0	585.87	1,601.10	2,186.97
7	100.0	557.97	1,524.86	2,082.83
8	100.0	531.40	1,452.25	1,983.65
9	100.0	506.09	1,383.09	1,889.19
10	100.0	481.99	1,317.23	1,799.22
11	100.0	459.04	1,254.51	1,713.55
12	100.0	437.18	1,194.77	1,631.95
13	100.0	416.37	1,137.87	1,554.24
14	100.0	396.54	1,083.69	1,480.23
15	100.0	377.66	1,032.08	1,409.74
16	100.0	359.67	982.94	1,342.61
17	100.0	342.54	936.13	1,278.68
18	100.0	326.23	891.55	1,217.79
19	100.0	310.70	849.10	1,159.80
20	100.0	295.90	808.67	1,104.57
20-Year Total		7,932.87	21,679.52	29,612.39
Equiv. Ann. Tot.		636.55	1,739.62	2,376.18

Source: Calculated from Table 40, using a 5 percent discount rate. Equivalent annual totals are calculated using a factor of 12.4622, to convert the 20 year totals into annual values.

Table 44. Total Cost Savings with a Fast Implementation Scenario.

Year	Implementation Rate (Percent)	Discounted Agency Savings (Million $)	Discounted Motorist Savings (Million $)	Total Discounted Savings (Million $)
1	100.0	747.73	2,043.46	2,791.19
2	100.0	712.13	1,946.15	2,658.27
3	100.0	678.21	1,853.48	2,531.69
4	100.0	645.92	1,765.21	2,411.13
5	100.0	615.16	1,681.16	2,296.32
6	100.0	585.87	1,601.10	2,186.97
7	100.0	557.97	1,524.86	2,082.83
8	100.0	531.40	1,452.25	1,983.65
9	100.0	506.09	1,383.09	1,889.19
10	100.0	481.99	1,317.23	1,799.22
11	100.0	459.04	1,254.51	1,713.55
12	100.0	437.18	1,194.77	1,631.95
13	100.0	416.37	1,137.87	1,554.24
14	100.0	396.54	1,083.69	1,480.23
15	100.0	377.66	1,032.08	1,409.74
16	100.0	359.67	982.94	1,342.61
17	100.0	342.54	936.13	1,278.68
18	100.0	326.23	891.55	1,217.79
19	100.0	310.70	849.10	1,159.80
20	100.0	295.90	808.67	1,104.57
20-Year Total		9,784.31	26,739.29	36,523.60
Equiv. Ann. Tot.		785.12	2,145.63	2,930.75

Source: Calculated from Table 40, using a 5 percent discount rate. Equivalent annual totals are calculated using a factor of 12.4622, to convert the 20 year totals into annual values.

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CHAPTER 4

LIFE-CYCLE EFFECTS OF SHRP PORTLAND CEMENT CONCRETE PRODUCTS

CONCRETE AND STRUCTURE RESEARCH

The highway industry consumes about 16 percent of the Portland cement used for construction in the United States. Despite the widespread use of concrete, research is needed on the product to improve its performance and to better understand the chemistry associated with hydration and hardening of Portland cement. Durability of Portland cement concrete remains a problem and a more complete understanding of the effects of additives is needed.

Annual bridge project obligations currently are about $3.5 billion. Bridge replacement accounts for $1.4 billion, new bridges $0.7 billion, major bridge rehabilitation $0.89 billion and minor bridge work $0.17 billion. These obligated levels are insufficient to satisfy future needs for bridge replacements, rehabilitation and maintenance.

OBJECTIVES

The objectives of the SHRP Portland cement and Portland cement concrete research were to increase the service life of concrete through an improved understanding of the chemistry of cement hydration, the properties of concrete and the performance of concrete in the highway environment.

The objectives of the structures research program were to provide methods to protect and rehabilitate existing chloride-contaminated concrete bridge components and to develop a decision model that will identify the most appropriate treatment for any structure under an agency's jurisdiction.

Research Projects

The proposed SHRP research on Portland cement and Portland cement concrete identified four projects:

1. chemistry and physics of cement and concrete,
2. durability of concrete,
3. quality control and condition analysis through nondestructive testing, and
4. mechanical behavior of concrete.

The results from these research projects were expected to give guidelines to improve Portland cement properties such as strength gain and curing and the durability of concrete in diverse climates using various additives.

SHRP research on structures identified four projects:

1. inspection and assessment of the physical condition of concrete structures,
2. protection and rehabilitation by electrochemical methods,
3. protection and rehabilitation by other than electrochemical methods, and
4. methodology for the protection and rehabilitation of bridges.

The results from these research projects were expected to determine how and when to protect bridges from corrosion to minimize life-cycle maintenance costs.

ACCOMPLISHMENTS

SHRP concrete and structures research and development produced 44 products that can be grouped into 10 areas as shown below.

Concrete Areas

- Concrete performance
- Alkali-silica reactivity
- Freezing and thawing resistance
- Non-destructive testing
- Concrete-strength tests
- Optimum highway-concrete technology

Structures Areas

- Diagnostic tools for concrete bridge physical condition assessment
- Concrete permeability tests
- Concrete sealers
- Concrete bridge protection and rehabilitation — other than electrochemical techniques

Twenty-four products were developed for concrete and 20 products for structures.

Concrete Products

Portland cement and Portland cement concrete products included handbooks for mixture design; guidelines for thermal effects; tests for recognition and mitigation of alkali-silica reactivity; tests and mitigation techniques for freeze-thaw; non-destructive tests for strength, air content and flaw detection, high-performance concrete; concrete strength tests and procedures for optimizing the properties and performance of Portland cement concrete.

Structures Products

Structures products included diagnostic tools, repair methods and guidelines for selecting appropriate rehabilitation and maintenance treatments for bridges. Some of the diagnostic tools, repair methods and guidelines for selecting appropriate rehabilitation and maintenance treatments for bridges included chloride content tester, permeability tests and corrosion rate tests. Repair methods included chloride removal, cathodic protection, rapid repair, marine structures and concrete removal. Guidelines for selecting appropriate rehabilitation and maintenance treatments were included in manuals and computer programs.

Post-SHRP Activities

Additional research, development and implementation activities resulted from the SHRP research on concrete and structures. Sponsored research and development by FHWA, state and industry included electrochemical chloride extraction, concrete curing relationships (curing tables) and mix design aggregate packing.

The major implementation efforts currently underway are funded by FHWA and state highway agencies. They include the five "showcase" workshops listed below.

- Assessment of Physical Condition and Concrete Structures
- Methodologies for Selection and Implementation of Bridge Protection and Rehabilitation Techniques
- Alkali-Silica Reactivity
- Concrete Durability
- High-Performance Concrete

Equipment loan programs were developed by FHWA for the impact echo device, alkali-silica reactivity field kit, ac impedance test, air-void analyzer and several non-destructive testing devices. Five states — Nebraska, New Hampshire, Ohio, Texas and Virginia — are designing or constructing bridges that contain high-performance concrete (9).

As of August 1995 AASHTO had adopted 16 SHRP concrete and structures products as provisional standards. The adoption of these test methods and techniques will increase their rate of implementation. Evaluation of the Portland cement and concrete products were performed (10).

EVALUATION OF THE PRODUCTS OF THE CONCRETE RESEARCH OF SHRP

The concrete research of the Strategic Highway Research Program (SHRP) consisted of six projects: C-201, *Concrete Microstructure*; C-202, *Eliminating or Minimizing Alkali-Silica Reactivity*; C-203, *Resistance of Concrete to Freezing and Thawing*; C-204, *Non-Destructive Testing for Quality Control/Condition Analysis of Concrete*; C-205, *Mechanical Behavior of High Performance Concrete*; and C-206, *Optimization of Highway Concrete Technology*. Every project produces several products. Some of them are newly proposed or modified test procedures, while others are specifications or guidelines. This report groups these products in six categories:

1) *Concrete Performance*, including products of C-201;

2) *Alkali-Silica Reactivity*, including products of C-202;

3) *Freezing and Thawing Resistance*, including products of C-203;

4) *Non-Destructive Testing*, including products of C-204;

5) *High Performance Concrete*, including a product of C-205;

6) *Concrete Strength Tests,* including three products of C-205; and

7) *Optimum Highway Concrete Technology*, including products of C-206.

The products of C-205 are grouped in two categories, because the concrete strength tests proposed by C-205 were not proposed specially for high performance concrete, and can also be applied to conventional concrete. SHRP Product 4001 is not a product of any of the six concrete research projects. However, it is included in Category 4 and evaluated, because it is listed with the products of C-204 in the same group in the SHRP Product Catalog.

Many of these SHRP products are not individually documented. Contrarily, they are explicitly or implicitly involved in related SHRP reports. On the back of the cover page of many reports numbers of some products are listed, but it does not mean that the report with a product number on the back of its cover page must include the content of the product. The reader is likely misled by these report numbers. When a report involves a product, the reader may have to manage to pick up and put together the contents diversely distributed in the report to “form” a product. Some products whose titles are announced in the catalog are even not described in any SHRP report. A better organization of the products is suggested to stimulate application of these costly research results.

1) Concrete Performance

Product 2005

Product 2005 is given in SHRP Report C-334 *A Guide to Determining the Optimal Gradation of Concrete Aggregates*. Although the product is named "Improving Concrete Mix Design," it should be understood as improving concrete mix design by optimal gradation of concrete aggregates, because only the factor of aggregate gradation is addressed in the report. This guideline supplies numerous packing tables for three different cases: two types of coarse aggregate, three types of coarse aggregate and sand and coarse aggregate, which provide convenience for users to determine the optimum amount of each mix element for a combination of up to four types of aggregate, where "optimum" means high density packing.

The objective of this product is just to seek geometrical high packing density for the concrete mix based on a mathematical model. The report does not relate the packing density to the concrete properties. A question arises naturally. Does the high packing density provide high quality of the concrete in all the aspects? The report does not discuss the effects of high density packing on concrete performance, either quantitatively or qualitatively. This product can be used as a reference in concrete mix design for high density packing, but the relationship between the packing density and other factors for the concrete mix design should be investigated in future research projects.

Product 2006

Product 2006 "Ensuring Crack-Free Curing of Concrete" is given in SHRP Report C-321 *A Guide to Evaluating Thermal Effects in Concrete Pavements*. The product takes the following parameters as input data: type of cementitious material, content of cementitious material, concrete temperature, air temperature, thickness of the pavement, etc. The user enters these parameters into the tables that the report provides, and then one of the following four symbols will be read as output:

- *, representing satisfactory thermal condition;
- TD, representing risk of differentials of temperature within the concrete slab that are too large;
- EF, representing risk of early freezing; and
- HT, representing risk of temperatures within the concrete slab that are too high.

It seems that some important parameters for thermal effects are neglected. For example, the product considers the radiation from the pavement to the sky, but ignores the solar radiation absorbed by the pavement. It considers the temperature differentials within the pavement slab, but ignores the absolute change in temperature of concrete with time. It is not clear how the product calculates thermal stresses in the pavement, including estimation of the coefficient of thermal expansion and constraints on pavement movement. No reliability analysis of output of the product is given.

Product 2007

Product 2007 provides a new laboratory test to measure concrete permeability. SHRP Report C-627 *Development of Transient Permeability Theory and Apparatus for Measurements of Cementitious Materials* gives a complete description about the mathematical model, equipment design, sampling handling and limitation of the equipment. The report should be considered an official document of SHRP Product 2007, but the term "Product 2007" does not appear through all the report. Many other SHRP reports print out numbers of the related SHRP products on the back cover pages. However, even on the back of the cover page of Report C-627, the term "Product 2007" does not show up. It is an example of disorganization of SHRP reports.

Permeability is a very important property parameter of concrete. It is recognized that transport of water and dissolved species occurs through a continuous network of pores, which exist in the cementitious matrix of concrete, as well as through the porosity which exist in the interfacial regions of aggregate. The mass transport severely affects initiation and development of many types of distresses including freezing and thawing attack and alkali-silica reactivity. The designed equipment measures the initial and boundary liquid pressure conditions, and permeability can be accurately calculated from pressure measurement.

To acknowledge this product, more tests should be run by different agencies. Since the cost of the prototype equipment was estimated as $15,000, it is suggested that several sets of the equipment should be made and distributed to different research centers for verification of this product.

Product 2008

Product 2008 was developed as a supplement to ASTM C-856 "Standard Practice for Petrographic Examination of Hardened Concrete." The ASTM standard gives details of how to use optical techniques for petrographic examination of hardened concrete. Product 2008 introduces fluorescent microscopy to the test standard. The use of an epoxy resin containing a fluorescent dye tends to enhance the ability to view porosity and mechanical features such as interface porosity and cracking. It requires a petrographic examination operator and is useful to highway engineers. The SHRP Product Category lists Product 2007 with the title "Diagnosing Performance Problems with Concrete," but does not reflect the nature of this product. Again, the term "Product 2008" never appears through SHRP Report C-662, which documents this product.

2) Alkali-Silica Reactivity

There are four SHRP products about Alkali-Silica Reactivity. Among them, Products 2010 and 2013 are for identifying alkali-silica reactivity (ASR), while Products 2009 and 2011 provide techniques to prevent from and mitigate ASR. Another SHRP product, Product 2017 "Designing ASR-Safe Concrete Mix," is included in the SHRP Product Catalog, but it is not available. This product was discontinued by the FHWA.

Products 2010 and 2013

Product 2010 is well organized as an illustrated handbook, "Handbook for the Identification of Alkali-Silica Reactivity in Highway Structures." (However, the handbook does not tell that it is a SHRP product and numbered 2010.) This handbook can be used to visually identify ASR-related damage. Since there are many causes to induce cracking in concrete, it is very important to distinguish ASR-induced cracking from damage by other factors, such as thermal effect, dry shrinkage effect, freezing and thawing and corrosion of reinforcing steel. The handbook presents colored photographs to show various appearances of ASR-induced cracking in pavement and bridge structures, which are very helpful to highway engineers and bridge inspectors in detecting ASR in concrete. Of course, a judgement that relies on visual perception cannot be sufficiently reliable for decision making in choosing proper rehabilitation strategy.

Product 2013, "Chemical Test for ASR Detection," can be used to confirm the presence of ASR once it has been visually detected by using Product 2010. The chemical test is simple. The concrete surface is treated with a uranyl acetate solution and viewed under ultraviolet light. The uranyl causes the ASR gel to fluoresce, imparting a greenish-yellow glow that can be clearly seen under the ultraviolet light. AASHTO T-299 specifies the test procedure.

Product 2011

In order to mitigate ASR in pavements and structures, Product 2011, "Mitigating ASR in Existing Concrete," provides several options to treat existing ASR, including drying the concrete and keeping it below 80 percent relative humidity, to stop further ASR expansion; applying restraint to counteract expansive ASR forces, which prevents further ASR expansion; bonding crack faces together with high density methacrylates and applying lithium compounds to the concrete. These methods were experimentally studied in the SHRP project in the laboratory. Some experimental pavements were installed and these installations are worth maintaining and monitoring for long-term effects of the mitigative measures.

Product 2009

To refrain from using potentially reactive aggregates, Product 2009, "Tools for Screening Reactive Aggregates," proposes to use a new standard test: the rapid immersion test method, ASTM C 1260-94 and AASHTO TP 14. This is the best test method available to screen potentially reactive aggregates. The Kansas State University recently completed a research project sponsored by the Kansas Department of Transportation to evaluate this test method, indicating: "the AASHTO TP 14 procedure has the potential to detect deleterious behavior of aggregates due to alkali-silica reactivity."

All these available SHRP products in Category 2 are described clearly and well documented. They are easily accessible and convenient for application.

3) Freezing and Thawing Resistance

Concrete is a porous material. With pores containing moisture, concrete is susceptible to damage under repeated cycles of freezing and thawing (or frost attack). SHRP Project C203 made efforts to improve existing AASHTO and ASTM standards for evaluating the resistance of concrete to frost attack and propose a test procedure for evaluating the resistance of aggregate to frost attack.

The current popular practice for evaluating the resistance of concrete to freezing and thawing is to use the standard AASHTO T-161 (ASTM C 666) test, which allows two test procedures. SHRP Product 2018 modifies AASHTO T-161 by suggesting a third test procedure to better simulate the natural freeze-thaw environment of concrete. By following ASTM C 215, AASHTO T-161 examines damage in concrete specimens by measuring the change in natural vibration (resonance) frequency. The 1985 version of the ASTM standard (ASTM C 215-85) uses sinusoidal excitation, but the 1991 version of the standard (ASTM C 215-91) also recommends impulse excitation as an alternate. SHRP Product 2019 recommends the impulse excitation as an AASHTO standard for high-accuracy measurement of the resonance frequency. The new test for identifying the durability of aggregate to freezing and thawing, called the Washington Hydraulic Fracture Test, is proposed as SHRP Product 2002.

Product 2002

The Washington Hydraulic Fracture Test provides a rapid and reliable test method for identifying D-cracking susceptible coarse aggregates. D-cracking is the term used to describe the distress in concrete that results from the disintegration of coarse aggregates after they have become saturated and have been subjected to repeated cycles of freezing and thawing. One of the notable causes to lead D-cracking is that the concrete contains coarse aggregates susceptible to D-cracking. Therefore, a test to screen aggregates for D-cracking potential is important. The test currently used for this purpose is AASHTO T-161, which requires a very long period of time (8-10 weeks). This new test takes only 8-10 days.

In the test, aggregates are submerged in water in a pressure chamber and subjected to a pressure of about 8 MPa (1150 psi). Under pressure, water enters the aggregate pores and compresses the air within the pores. When the pressure is rapidly released, the air compressed in the aggregate pores forces the water out; if the aggregate fractures or fragments, it indicates a susceptibility. A primary value determined from testing is the percentage of fractures, which is then used to calculate a value called the hydraulic fracture index (HFI). Aggregates with high (80 to 100 or higher) HFI values tended to be non-D-cracking susceptible, while aggregates with low (less than about 60) HFI values tended to be D-cracking susceptible.

As SHRP Report C391 states, “theoretically, the test should be able to simulate the hydraulic pressures that many believe cause D-cracking in nondurable aggregates.” The report does not address this assumed theoretical background to support this understanding. However, reliability and repeatability were verified by tests. The SHRP project conducted the proposed tests on aggregates from many different sources. These aggregates were also identified by the existing AASHTO standard tests. Test results showed that, with the exception of one limestone, all the D-cracking susceptible aggregates had HFI values below 60; while all the non D-cracking susceptible aggregates had high HFI values.

As indicated in SHRP Report C391, for aggregates that absorb water extremely quickly, the high absorption rate could prevent the above fracture mechanism from working. The procedure suggest that the aggregates be treated with a silane-based sealer to make the pores hydropholic rather than hydrophilic to reduce the absorption rate. It is uncertain how this treatment can make this test successful.

The main part of the testing apparatus is the pressure chamber. Cost of it is high.

Product 2018

AASHTO T-161, "Resistance of Concrete to Rapid Freezing and Thawing," (or ASTM C 666) allows two procedures to simulate freezing and thawing cycles: Procedure A, Rapid Freezing and Thawing in Water and Procedure B, Rapid Freezing in Air and Thawing in Water. As SHRP Product 2018, the modification of AASHTO T-161 allows a third procedure. Procedure C consists of wrapping specimens with absorbent cloth to keep the specimens wet during freezing. The modification is in response to criticisms of Procedures A and B.

Procedure A uses a container that allows the specimen to be surrounded by "not less than 1/32 in. (1 mm) nor more than 1/8 in. (3 mm) of water at all times." Accordingly, ice pressure builts up between the container wall and the specimen. This ice pressure may damage the specimen. Generally, the use of a container results is non-uniform pressures on the specimen. The primary objection to Procedure B is that the specimen is allowed to dry during freezing, which slows the accumulation of damage.

Tests showed that Procedure C provided the most rapid damage due to freezing and thawing. In other words, it provided the most severe conditions. However, a question arises very naturally: does the wet cloth wrapping give the specimen a certain condition? Moisture and heat transfer through the wet cloth must vary with many factors such as type and properties of the cloth, contact between the cloth and specimen, etc. It seems that the boundary condition of the specimen provided by the cloth is hardly quantitatively described. Therefore, test results may vary from laboratory to laboratory. Until now, sufficient data have not been obtained to conclude that this test procedure is more realistic than Procedures A and B. Equipment for this test procedure is easy to acquire but requires considerable maintenance.

Product 2019

A test method "Fundamental Transverse Frequency and Quality Factor of Concrete Prism Specimens" is proposed as SHRP Product 2019. As stated above, AASHTO T-161 originally uses sinusoidal excitation method (ASTM C 215-85) to examine damage in concrete prisms, but ASTM C 215 has been revised in 1991 to include impulse excitation as an alternate method (ASTM C 215-91). The proposed test method is a method using impulse to induce transverse vibration of the concrete prism specimen. However, in ASTM C 215-91, all transverse, longitudinal and torsional modes of vibration in the cylindrical or prismatic specimen are included, whereas the proposed test procedure suggests transverse vibration in the prismatic specimen only. Comparatively, the proposed test procedure regulates the apparatus in more detail, including Fourier analyzer, impact hammer, accelerometer and power supply, specimen support and data analysis and control equipment.

The proposed test procedure requires the Fourier analyzer of a maximum frequency capability greater or equal to 8 kHz, whereas ASTM C 215 requires 20 kHz. A lower frequency band is allowed for only transverse vibration of the prismatic specimen because the natural (or resonance) frequency of the same concrete specimen (either prismatic or cylindrical) in transverse vibration is lower than in longitudinal vibration, and the natural frequency of a 152 × 152 × 710 or 102 × 102 × 510-mm prism in transverse vibration is lower than that of a 152 × 305-mm concrete cylinder. For the comparisons, see Chapter 6, "Resonant Frequency Methods," by V. M. Malhotra and V. Sivasundaram of the book *CRC Handbook on Nondestructive Testing of Concrete*, edited by V. M. Malhotra and N. J. Carino.

When sinusoidal excitation is used, the specimen should be forced to vibrate at varying frequencies. At every frequency, the amplitude of the specimen vibration should be recorded. After a series of tests, the natural frequency can be determined at the maximum reading of the amplitude. When the impulse excitation method is used, only one test is needed. After the specimen is struck by an impact hammer, the time response of the specimen should be recorded. This time response (a signal in time domain) is converted into a frequency response (a signal in frequency domain) by the Fast Fourier Transform (FFT) technique. The resonance frequency is the frequency with the highest peak in the frequency response (or amplitude spectrum). With the impulse excitation method, the test procedure is very simple and precise results are obtained.

The FFT technique and the Fourier analyzer have been available for a long time. It is proper to introduce them to the test standard.

Product 2004

Three SHRP products, listed in the SHRP Product Catalog and other documents, outline specifications or methods for improving freezing and thawing conditions. They are Product 2004, "Mitigating D-Cracking in Existing Concrete," Product 2021, "Aggregates Durability Specifications," and Product 2020, "Air Entrainment Specifications." The first product avoids or minimizes further damage of in-service concrete evidencing D-cracking problems, whereas the latter two describe mix design of new concrete with higher resistance to frost attack. However, Products 2020 and 2021 are not available. As claimed in SHRP Report C391, “no frost-resistance modeling has been attempted at this time, although Report C391 is the only report under Contract C203".

For mitigating D-cracking in existing concrete, SHRP Report C391 summarizes causes of D-cracking. Although the mechanisms of D-cracking have not yet been completely clarified, it has been observed that D-cracking occurs under the following conditions: (1) the concrete contains aggregates susceptible to D-cracking, (2) the concrete is exposed to sufficient moisture and (3) the concrete is exposed to repeated cycles of freezing and thawing. However, for existing concrete, change in the intrinsic properties of the aggregates used in the concrete has been found unlikely.” Therefore, the remaining methods of mitigating D-cracking in existing concrete can only be: (1) to eliminate or reduce the moisture condition and (2) to eliminate or reduce the freezing condition. Various protective options were reviewed, but only the method that uses penetrating sealers to reduce the moisture in concrete was promising. Four concrete sealers were identified as having good potential for use in delaying the onset of aggregate-related D-cracking.

This study conducted the first field study to observe the effectiveness of concrete sealers for mitigating D-cracking in existing concrete pavement constructed using nondurable aggregates. As summarized in Report C391, “the field tests and laboratory tests of field test materials will provide a great deal of information that will be useful to validate the models and concepts presented in parts I and II of this report.” It seems that more research is required to reach solid conclusions.

4) Non-Destructive Testing

Three products deal with nondestructive tests for quality control of concrete. They are Product 2010, “Detecting Concrete Flaws and Delimitation,” Product 2022, “Measuring Concrete Strength and Maturity in the Field,”and Product 4001, “Measuring Air Entrainment with the Fiber Optic Air Meter.” Although Products 2010 and 4001 are not reported in any SHRP reports, information about Product 4001 is available in “Strategic Highway Research Program Products,” Proceedings of a Specialty Conference, sponsored by the Highway Division of the American Society of Civil Engineers and the Federal Highway Administration, Denver, Colorado, April 8-10, 1991. Product 2022 is reported in SHRP Report C376, “Filed Manual for Maturity and Pullout Testing on Highway Structures.”

Product 2022

In SHRP Report C376, the project researchers provided guidance on the use of maturity testing and pullout testing for measuring in-situ strength of concrete pavement and structures at early ages. The maturity method accounts for the combined effects of time and temperature on the strength development of concrete. By measuring the temperature of the concrete during the curing period, personnel estimate the strength at any particular age. Pullout testing is performed by using metal disks (or inserts) installed within the formwork prior to concrete placement. To measure the in-situ strength, a loading apparatus is used to measure the force required to extract the insert from the concrete mass. The measured force is used to estimate the in-situ strength by correlation relationship established in the previous research. Either the maturity or the force for pullout is measured in field. The strength estimated by either test method is expected more accurate than the strength measured from the specimens prepared beside the concrete pavement or structure. The in-situ test procedure for either method was previously proposed in ASTM standards and/or the ACI committee report.

The contribution of the SHRP product to the techniques was to suggest combination of these two test methods for field use. It was recommended that the strength-maturity relationship be obtained by laboratory tests of the cylindrical compressive-strength specimens prepared with the same mix design which was planned for the concrete pavement of structure. For non-structural members, it was suggested that the in-situ strength be estimated by the measured maturity and the strength-maturity relationship. For structural members, it was suggested that cylindrical specimens of the same mix design were prepared besides the members. These specimens should be tested for compressive strength to adjust the strength estimated by the maturity method. Combination of the maturity method and pullout test was also suggested for structural members. In the combined method, the relationship between the pullout strength and compressive strength should be obtained in advance. The pullout strength would be predicted for a specific time from the compressive strength-maturity and pullout strength-compressive strength relationships. Then an in-situ pullout test should be conducted to verify the predicted pullout strength for the purpose of quality control.

The maturity test method has been continuously developed since Product 2022 appeared. Many progresses have been made in measuring of maturity and techniques for correlating maturity and strength. A simple method has been developed by TTI researchers, referred to as “one-graph” method. This method combines data from lab tests and field tests in a single graph to predict the strength of concrete pavement or structure in field. The maturity method is a very promising nondestructive test method for concrete quality control/assurance. Use of pullout test enhances the reliability of the strength prediction by the maturity method. However, it is well known that data from pullout tests are often largely scattered. The report does not provide error analysis of the pullout method. Further research is necessary to provide a step by step test procedure and a test data variability process.

Product 4001

A fiber optic apparatus was developed to determine the air content of freshly mixed concrete in situ so as to facilitate acceptance or rejection in the field. Content of air in concrete is a very important factor for freeze-thaw durability control. Although standardized test methods for measuring air content in concrete have existed for a long time, the air content measured by these methods sometimes cannot present the air content in the pavement or structure because the test sample is prepared and the pavement or structure are placed with different mixing processes. The newly developed test method measures the air content in the pavement or structure of interest directly.

This apparatus detects the air content by changes in the intensity of reflected light transmission through a thin optical fiber. Intensity changes occur due to differences in the index of refraction between an air bubble and concrete. A diode laser provides the optical signal. Reflected light intensity signal is converted to an electrical current by a photo detector. Reliability of the apparatus was examined, but, no report about it is available.

5) High Performance Concrete

Product 2014

A series of laboratory investigations of the mechanical behavior and field installations of high performance concrete were performed under SHRP Contract C-205. The main product of the research project was Product 2014, “Specifications for High-Performance Concrete.” Other products from this projects include three test procedures for determining modulus of rupture, compressive strength and interfacial bond shear strength, respectively. Since these test procedures can also be used for “conventional” concrete, they are evaluated under Category 6)

Concrete Strengths Tests.

The six-volume research report “Mechanical Behavior of High Performance Concretes” supplies abundant laboratory test results for high performance concrete, which is defined as concrete with much higher early strength and greatly enhanced durability against freezing and thawing in comparison with conventional concrete. These test results can be used as guidelines for mix design, mixing and curing procedures. However, the report does not claim that the research has provided specifications for the high performance concrete, although the term “specifications” is used in the SHRP Product Catalog. The report categories high performance concrete (HPC) into four types: very early strength concrete (VES), high early strength concrete (HES), very high strength concrete (VHS), and high early strength fiber reinforced concrete (HESFRC). Detailed information for each type of HPC related to mix designs, methods of proportion and strength and durability is summarized in different volumes of the report. Potential applications of these types of HPC are proposed, but, no field tests were conducted in this project.

Economic benefits from using HPC in building and repairing pavement, bridges and other structures should be great, but no quantitative estimation of the benefits is possible at this moment before field investigations. Research for application of HPC and observation of its long-term performance in service is necessary.

6) Concrete Strength Tests

Three concrete strength test procedures were proposed under Contract C-205. They are Product 2023, “Flexural Strength Test,” Product 2024, “Compressive Strength Test,” and Product 2025, “Interfacial Bond Test.”

Product 2023

ASTM C-78 has been extensively used for determining flexural strength (or modulus of rupture). SHRP Product 2023 suggests using a fixture (or mounting frame) to measure tensile strain and midspan deflection in the flexural test. The test procedure specified by ASTM C-78 is intact. The loading rate used in the SHRP project was 800 lb/min. It can be calculated that this loading rate supplies an increasing rate of the maximum tensile stress in the specimen as 150 psi/min, which is the middle value of the range of the stress rate specified in the ASTM standard: 125-175 psi/min. It is worth clearly pointing out that, when no strain or deflection measurement is required, the expensive fixture is not needed and the flexural strength should be determined simply following ASTM C-78.

Many different instrumentations have been proposed in research for measuring the strain and deflection. If a test standard is needed for determining the strain and deflection, all these existing instrumentation methods should be evaluated and compared for selection. When a displacement is recorded, the displacement signal can be fed back to the testing machine in order to control the test. Then the catastrophic failure of the specimen can be avoided, when the peak load is reached, and, therefore, the softening part of the stress-strain curve can be acquired. In such a way, more information of the mechanical behavior of the specimen can be obtained in a single test with no additional hardware required.

Product 2024

As for compressive strength, ASTM C-39 is widely used. Product 2024 proposes use of steel caps with neoprene pads instead of sulfur caps. This alternative of specimen capping technique has actually been proposed by AASHTO T-22. Product 2024 suggests use of the linear voltage differential transducers (LVDTs) to measure the length change of the specimen. Since measurement of the compressive strength does not need the displacement, it is not a modification of ASTM C-39, as claimed in SHRP Product Catalog and related SHRP Reports. It can, however, be considered an advance from ASTM C-469. ASTM C-469 uses a compressometer and an extensometer to measure the dimensional change of the specimen during the compression test for determining the modulus of elasticity and the Poisson ratio. The ASTM standard does not require automatic recording of data from the compressometer and extensometer. Instead, data can be read manually through the dial gage. As the electronic technology develops, automatic recording of data is more likely. Product 2024 does not measure the lateral expansion of the specimen so it does not measure the Poisson ratio.

Product 2025

Product 2025 proposes a test procedure for determining the shear strength of the interfacial bond between bonded faces. The specimen is designed to have a direct shear condition. This can be considered a supplement to ASTM C-1042, which provides the bond interface with a shear plus compression stress state. However, the cost of an ASTM C-1042 test is very little compared with that of the shear test specified by Product 2025. Data scatter of the shear test may be severe. Researchers should be cautious in applying this test before the precision of the test is analyzed. Report SHPR C-361 states no precision criterion for the shear test.

The direct shear test was designed to estimate the bond strength of concrete overlay to the existing concrete pavement. However, the pure shear stress state hardly exists in the bond interface. Since failure occurs in complex stress states indeed, with only the shear strength determined by a direct shear test, a failure criterion cannot be established. A Mohr-Coulomb type (or Drucker-Prager) criterion is required. Further efforts are necessary to design tests for sufficient data with low cost.

7) Optimum Highway Concrete Technology

Two new test methods were developed for monitoring properties of concrete freshly mixed in field. Those are Products 2027 and 2028, where two AASHTO test standards were proposed as AASHTO TP 23, “Water Content of Freshly Mixed Concrete Using Microwave Oven Drying,” and AASHTO TP 24, “Density of Freshly Mixed Concrete in Place By a Twin-Probe Nuclear Method.” Product 2039, “HWYCON-An Expert System for Concrete Durability,” is a computer program to assist state highway department staff in obtaining available knowledge of highway concrete.

Products 2027 and 2028

These two newly proposed tests are very useful for quality control and quality assurance of concrete in field. The amount of water in the concrete mix affects the quality of concrete during placement and the durability of the hardened concrete. Field conditions cannot assure the concrete mix containing the amount of water as specified by the mix design without monitoring of water content. Product 2027 improves microwave oven drying technique and raises the efficiency of the water content test. Testing can be completed in 14 to 16 minutes. The information obtained from the fast testing can be fed to the concrete plant to control the concrete quality. Although a test standard has been proposed, SHRP Report C-373 “recommends that the method be adopted by agencies on a trial basis so that it may be further evaluated with a wider variety of materials and conditions than could have been included in the limited test program described in this report.”

The mixing process (or mechanical internal vibration of the mix) in field is different from that in the laboratory. The measurement of in-place density of freshly mixed concrete helps achieve proper consolidation. The nuclear radiation technology used in the product is based on decreasing in radiation intensity with the thickness and density of the material. However, SHRP Report C-414 points out: "The equipment, electronics, and testing procedures in the gauges may be modified in the future by the manufacturer for more convenient use during construction."

Product 2039

Product 2039 (HWYCON) contains knowledge in three areas: 1) diagnostic-distress identification and causes of distresses, 2) material selection for construction and reconstruction and 3) repair and rehabilitation recommendations on materials and procedures for concrete pavement repair and rehabilitation. With advancing of highway concrete research, this expert system needs to keep current to include all the newly developed knowledge.

CALCULATION OF AGENCY SAVINGS FROM IMPROVED CONCRETE PRODUCTS DEVELOPED WITH SHRP

While several SHRP products came out to improve the construction, performance and life of concrete pavements and structures, very little has been implemented at this time. This creates a significant problem in making estimates of potential cost savings that may be generated in the future as improvements are made to existing techniques and tests. A rough estimate of the potential savings of several SHRP products are given in Table 45. These estimates are based upon the best engineering judgement and information available at the current time. The numbers represent savings solely in reconstruction of concrete pavements and structures and do not take into account any improvement in pavement life or structure life.

The annual potential net savings, given in Table 45, is estimated to be $46.61 million. These savings can be captured only by implementation by the state DOTs throughout the United States. This implementation process is anticipated to be a slow, gradual process as field tests are conducted in limited areas, procedures modified as needed and adoption increased by other agencies based upon those successes. Conservative implementation scenarios are used similar to those that are used for preventative maintenance and pothole repair. Three implementation scenarios are estimated; a slow implementation scenario with implementation reaching 25 percent after 20 years, a moderate implementation scenario with 50 percent implementation after 20 years, and a fast implementation scenario with 100 percent implementation after 20 years. The results of these three scenarios are given in Tables 46, 47 and 48. These tables show that substantial savings can be generated from even these modest implementation scenarios, ranging from a total of $51 million to $192 million over 20 years.

Table 45. Estimated Agency Cost Savings of SHRP Concrete Products

Product	Total Savings (Million $)	Implem. Cost (Million $)	Net Savings (Million $)
Maturity Meter[1]	20.00	1.00	19.00
Wash Fracture Test[1]	20.00	1.50	18.50
F/T Test - Proced. C[1]	200.00	0.01	199.99
D-Crack Guidelines[1]	50.00	0.10	49.90
Permeameter[1]	200.00	5.00	195.00
ASR Treatment[1]	100.00	1.50	98.50
20 Year Total[1]	590.00	9.11	580.89
Annual Total[2]	47.34	0.73	46.61

[1] Numbers represent the 20 year present worth of the savings and costs assuming full implementation over that period.

[2] Annual totals are calculated using a present worth factor of 12.4622, to convert the 20 year totals into equivalent annual values.

Table 46. Total Concrete Cost Savings with a Slow Implementation Scenario.

Year	Implementation Rate (Percent)	Discounted Agency Savings (Million $)
1	1.0	0.47
2	1.3	0.58
3	1.8	0.76
4	2.4	0.97
5	3.1	1.19
6	4.0	1.46
7	4.9	1.70
8	5.9	1.95
9	7.1	2.24
10	8.3	2.49
11	9.6	2.75
12	11.0	3.00
13	12.5	3.24
14	14.0	3.46
15	15.7	3.70
16	17.4	3.90
17	19.2	4.10
18	21.0	4.27
19	23.0	4.45
20	25.0	4.61
20-Year Total		51.29
Equiv. Annual Total		4.12

Source: Calculated from Table 44, using a 5 percent discount rate. Equivalent annual totals are calculated using a factor of 12.4622, to convert the 20 year totals into annual values.

Table 47. Total Concrete Cost Savings with a Moderate Implementation Scenario.

Year	Implementation Rate (Percent)	Discounted Agency Savings (Million $)
1	1.0	0.47
2	1.7	0.75
3	2.7	1.14
4	3.9	1.57
5	5.4	2.07
6	7.1	2.59
7	9.0	3.13
8	11.1	3.68
9	13.4	4.23
10	15.9	4.78
11	18.5	5.29
12	21.4	5.83
13	24.4	6.33
14	27.6	6.82
15	30.9	7.27
16	34.4	7.71
17	38.1	8.14
18	41.9	8.52
19	45.9	8.89
20	50.0	9.22
20-Year Total		98.44
Equiv. Annual Total		7.90

Source: Calculated from Table 44, using a 5 percent discount rate. Equivalent annual totals are calculated using a factor of 12.4622, to convert the 20 year totals into annual values.

Table 48. Total Concrete Cost Savings with a Fast Implementation Scenario.

Year	Implementation Rate (Percent)	Discounted Agency Savings (Million $)
1	1.0	0.47
2	2.4	1.07
3	4.3	1.82
4	6.8	2.74
5	9.8	3.76
6	13.3	4.86
7	17.1	5.95
8	21.4	7.09
9	26.0	8.20
10	31.0	9.31
11	36.4	10.42
12	42.2	11.50
13	48.3	12.54
14	54.7	13.52
15	61.5	14.48
16	68.6	15.38
17	76.0	16.23
18	83.7	17.02
19	91.7	17.76
20	100.0	18.45
20-Year Total		192.54
Equiv. Annual Total		15.45

Source: Calculated from Table 44, using a 5 percent discount rate. Equivalent annual totals are calculated using a factor of 12.4622, to convert the 20 year totals into annual values.

Agency and Motorist Cost Savings of Improved Concrete Pavements

Several factors can contribute to concrete pavements requiring rehabilitation prematurely. The most significant factors are D-cracking and ASR problems. The SHRP research has developed products to combat these problems, and this analysis is an attempt to quantify the cost savings of extending pavement life for those concrete pavements experiencing premature failure. For purposes of this analysis, concrete pavements that experience these problems require rehabilitation after 10 years. Using the SHRP products, that life before rehabilitation is extended to 17 years. It is estimated that about 20 percent of concrete pavements are affected by premature failure. Therefore in this analysis, 20 percent of the rigid pavements in the U.S., excluding the local functional class, are used to estimate the potential benefits. These mileage totals are shown in Table 49. It should be pointed out that there has been very little implementation thus far of SHRP products in the concrete pavement area. Therefore the assumed increased pavement life of 7 years as well as it affecting 20 percent of the concrete pavements is purely speculative. However, those assumptions are the best guess of the research team experts, based upon available information. Further research should be directed to determine the anticipated impacts of SHRP products in this area, and more specifically to determine the appropriate assumptions to use in this type of analysis.

Table 50 gives the calculated PSI values for each highway type over a 40 year analysis period. A 40 year analysis period was chosen because it is consistent with the other computer calculations of SHRP products and allows enough time to pass that each scenario goes through at least two life cycles.

The highway type categories from Table 49 and the MicroBENCOST PC computer program were used to make cost savings estimates of the concrete pavement scenarios. In addition an annual traffic growth rate of 2.1 percent was assumed, consistent with the other SHRP product computer runs.

The results of the analysis for each highway type are given in Table 51. Detailed MicroBENCOST output are given in Appendix D. The agency cost savings consist of fewer required rehabilitations for over the 40 life cycle in the analysis. The motorist cost savings are broken down into two categories, delay savings and reduction in vehicle operating costs (VOC). As expected, the greatest savings are for the higher volume facilities and much lower savings for the low-volume highways. The urban freeway, for example, would generate more than $1.64 million dollars per mile in motorist savings and $390 thousand per mile in agency savings. In contrast the rural 2-lane undivided highway would be about $79 thousand in motorist savings and $66 thousand in agency savings.

In order to compare the cost savings, it is necessary to convert the total savings per mile in Table 51 to an annual cost savings. This can be done using equivalent uniform annual cost factors. The factor for a uniform series over 40 years using a 5 percent discount rate is 17.16. By dividing each number in Table 51 by 17.16, they can be converted into annual savings. These annual numbers are given in Table 52. The numbers range from $118,797 for an urban freeway to $8,457 for a rural 2-lane highway.

These annual cost savings per mile can then be aggregated using the total asphalt mileage that could potentially benefit from the improved design equations. As mentioned above 20 percent of the total rigid pavement highways in the U.S. is used to calculate the total savings. The total annual cost savings are given in Table 53. This table shows that a total of about $578 million could be saved annually in the U.S. using the SHRP products to increase the life of concrete pavements. Of this total, about $145 million would represent annual agency savings, and $432 million represents annual motorist savings.

The numbers in Table 53 represent the total potential annual savings if all agencies immediately implemented the improved maintenance strategies. These savings can only be realized with full implementation through all state and local transportation agencies in the U.S. That implementation process is expected to be a slow, gradual process as case studies are tried and improvements made to the existing recommendations. Tables 54, 55, and 56 give estimates of the total estimated benefits over 20 years assuming a slow implementation scenario, a moderate implementation scenario and a fast implementation scenario. The slow implementation scenario assumes a 25 percent implementation after 20 years, the moderate implementation scenario assumes a 50 percent implementation after 20 years, and the fast implementation scenario assumes a 100 percent implementation occurring after 20 years. These scenarios give a reasonable range for the expected benefits to the improved maintenance strategies as developed in SHRP. The potential cost savings are substantial, even with these very modest implementation scenarios, ranging from $636 million to $2.38 billion over the next twenty years. The savings to agencies alone would range from $160 to $601 million in present value dollars.

Table 49. U.S. Rigid Pavement Mileage

	Total Mileage	20% Affected Mileage
Urban		
Freeways	12,952	2,590
4-Lane Divided	6,152	1,230
2-Lane Undivided	10,990	2,198
Total	30,095	6,019
Rural		
Freeways	11,551	2,310
4-Lane Divided	1,859	372
2-Lane Undivided	21,108	4,222
Total	34,519	6,904
Overall Total	64,614	12,923

Source: *Highway Statistics*, 1994 (1), Table HM-57, pp. V46-V47, and Table HM-50, pp. V36-V37.

Table 50. Yearly PSI Values Used for Improved Concrete Pavements.

Year	Freeway		4-Lane Divided		2-Lane Undivided	
	Current Condition	Improved Condition	Current Condition	Improved Condition	Current Condition	Improved Condition
1	4.30	4.30	4.20	4.20	4.00	4.00
2	4.29	4.30	4.19	4.20	3.99	4.00
3	4.27	4.30	4.16	4.20	3.96	4.00
4	4.21	4.29	4.10	4.19	3.89	3.99
5	4.12	4.28	4.00	4.18	3.77	3.98
6	3.98	4.26	3.86	4.16	3.61	3.96
7	3.81	4.24	3.67	4.13	3.40	3.92
8	3.59	4.20	3.44	4.09	3.13	3.88
9	3.32	4.15	3.15	4.04	2.80	3.81
10	3.00	4.08	2.80	3.97	2.40	3.73
11	4.30	4.00	4.20	3.87	4.00	3.63
12	4.29	3.89	4.19	3.76	3.99	3.50
13	4.27	3.77	4.16	3.63	3.96	3.35
14	4.21	3.62	4.10	3.47	3.89	3.16
15	4.12	3.44	4.00	3.28	3.77	2.94
16	3.98	3.24	3.86	3.05	3.61	2.69
17	3.81	3.00	3.67	2.80	3.40	2.40
18	3.59	4.30	3.44	4.20	3.13	4.00
19	3.32	4.30	3.15	4.20	2.80	4.00
20	3.00	4.30	2.80	4.20	2.40	4.00
21	4.30	4.29	4.20	4.19	4.00	3.99
22	4.29	4.28	4.19	4.18	3.99	3.98
23	4.27	4.26	4.16	4.16	3.96	3.96
24	4.21	4.24	4.10	4.13	3.89	3.92
25	4.12	4.20	4.00	4.09	3.77	3.88
26	3.98	4.15	3.86	4.04	3.61	3.81
27	3.81	4.08	3.67	3.97	3.40	3.73
28	3.59	4.00	3.44	3.87	3.13	3.63
29	3.32	3.89	3.15	3.76	2.80	3.50
30	3.00	3.77	2.80	3.63	2.40	3.35
31	4.30	3.62	4.20	3.47	4.00	3.16
32	4.29	3.44	4.19	3.28	3.99	2.94
33	4.27	3.24	4.16	3.05	3.96	2.69
34	4.21	3.00	4.10	2.80	3.89	2.40
35	4.12	4.30	4.00	4.20	3.77	4.00
36	3.98	4.30	3.86	4.20	3.61	4.00
37	3.81	4.30	3.67	4.20	3.40	4.00
38	3.59	4.29	3.44	4.19	3.13	3.99
39	3.32	4.28	3.15	4.18	2.80	3.98
40	3.00	4.26	2.80	4.16	2.40	3.96

Table 51. Discounted Cost Savings per Mile over a 40 Year Analysis Period (Thous. $)

	Urban			Rural		
	Freeway	4-Lane Divided	2-Lane Undiv	Freeway	4-Lane Divided	2-Lane Undiv
Agency Cost Savings						
Total	390.00	267.00	152.00	209.00	168.00	66.00
Motorist Cost Savings						
Delay	375.43	110.73	197.70	93.79	36.33	24.71
VOC	1,273.01	369.83	220.17	445.02	131.50	54.40
Total	1,648.44	480.56	417.87	538.81	167.83	79.11
Total Cost Savings	2,038.44	747.56	569.87	747.81	335.83	145.11

Source: Output from MicroBENCOST program.

Table 52. Equivalent Uniform Annual Cost Savings per Mile ($).

	Urban			Rural		
	Freeway	4-Lane Divided	2-Lane Undiv	Freeway	4-Lane Divided	2-Lane Undiv
Agency Cost Savings						
Total	22,728	15,560	8,858	12,180	9,791	3,846
Motorist Cost Savings						
Delay	21,879	6,453	11,522	5,466	2,117	1,440
VOC	74,189	21,553	12,831	25,933	7,664	3,170
Total	96,068	28,006	24,353	31,401	9,781	4,610
Total Cost Savings	118,797	43,566	33,211	43,581	19,572	8,457

Source: Calculated from Table 49.

Table 53. Total Annual Cost Savings (Million $)

	Urban			Rural			Total
	Frwy	4-Ln Div	2-Ln Undiv	Frwy	4-Ln Div	2-Ln Undiv	
Agency Cost Savings							
Total	58.87	19.14	19.47	28.14	3.64	16.24	145.49
Motorist Cost Savings							
Delay	56.67	7.94	25.32	12.63	0.79	6.08	109.42
VOC	192.15	26.51	28.20	59.91	2.85	13.39	323.01
Total	248.82	34.45	53.53	72.54	3.64	19.47	432.43
Total Cost Savings	307.68	53.59	73.00	100.67	7.28	35.70	577.92

Source: Calculated from Table 50, using the affected mileage in Table 49.

Table 54. Total Cost Savings with a Slow Implementation Scenario.

Year	Implementation Rate (Percent)	Discounted Agency Savings (Million $)	Discounted Motorist Savings (Million $)	Total Discounted Savings (Million $)
1	1.0	1.45	4.32	5.78
2	1.3	1.80	5.35	7.16
3	1.8	2.38	7.06	9.44
4	2.4	3.02	8.97	11.98
5	3.1	3.71	11.03	14.74
6	4.0	4.56	13.55	18.11
7	4.9	5.32	15.81	21.13
8	5.9	6.10	18.13	24.23
9	7.1	6.99	20.78	27.77
10	8.3	7.78	23.14	30.92
11	9.6	8.57	25.49	34.06
12	11.0	9.36	27.81	37.17
13	12.5	10.13	30.10	40.23
14	14.0	10.80	32.11	42.91
15	15.7	11.54	34.29	45.83
16	17.4	12.18	36.19	48.37
17	19.2	12.80	38.04	50.83
18	21.0	13.33	39.62	52.95
19	23.0	13.90	41.33	55.23
20	25.0	14.39	42.78	57.18
20-Year Total		160.12	475.90	636.01
Equiv. Ann. Tot.		12.85	38.19	51.04

Source: Calculated from Table 53, using a 5 percent discount rate. Equivalent annual totals are calculated using a factor of 12.4622, to convert the 20 year totals into annual values.

Table 55. Total Cost Savings with a Moderate Implementation Scenario.

Year	Implementation Rate (Percent)	Discounted Agency Savings (Million $)	Discounted Motorist Savings (Million $)	Total Discounted Savings (Million $)
1	1.0	1.45	4.32	5.78
2	1.7	2.36	7.00	9.36
3	2.7	3.56	10.59	14.15
4	3.9	4.90	14.57	19.47
5	5.4	6.46	19.21	25.67
6	7.1	8.09	24.06	32.15
7	9.0	9.77	29.04	38.81
8	11.1	11.48	34.11	45.59
9	13.4	13.20	39.22	52.42
10	15.9	14.91	44.32	59.23
11	18.5	16.52	49.11	65.64
12	21.4	18.20	54.11	72.31
13	24.4	19.77	58.75	78.52
14	27.6	21.30	63.29	84.59
15	30.9	22.71	67.49	90.19
16	34.4	24.07	71.55	95.63
17	38.1	25.39	75.48	100.87
18	41.9	26.60	79.05	105.65
19	45.9	27.75	82.47	110.22
20	50.0	28.79	85.56	114.35
20-Year Total		307.29	913.32	1,220.62
Equiv. Ann. Tot.		24.66	73.29	97.95

Source: Calculated from Table 53, using a 5 percent discount rate. Equivalent annual totals are calculated using a factor of 12.4622, to convert the 20 year totals into annual values.

Table 56. Total Cost Savings with a Fast Implementation Scenario.

Year	Implementation Rate (Percent)	Discounted Agency Savings (Million $)	Discounted Motorist Savings (Million $)	Total Discounted Savings (Million $)
1	1.0	1.45	4.32	5.78
2	2.4	3.33	9.88	13.21
3	4.3	5.67	16.87	22.54
4	6.8	8.55	25.40	33.95
5	9.8	11.73	34.86	46.60
6	13.3	15.16	45.06	60.22
7	17.1	18.57	55.18	73.74
8	21.4	22.13	65.77	87.89
9	26.0	25.60	76.10	101.70
10	31.0	29.07	86.41	115.49
11	36.4	32.51	96.63	129.15
12	42.2	35.90	106.70	142.59
13	48.3	39.13	116.30	155.43
14	54.7	42.21	125.44	167.65
15	61.5	45.19	134.32	179.51
16	68.6	48.01	142.69	190.70
17	76.0	50.66	150.56	201.21
18	83.7	53.13	157.92	211.05
19	91.7	55.44	164.77	220.21
20	100.0	57.58	171.13	228.70
20-Year Total		601.02	1,786.32	2,387.33
Equiv. Ann. Tot.		48.23	143.34	191.57

Source: Calculated from Table 53, using a 5 percent discount rate. Equivalent annual totals are calculated using a factor of 12.4622, to convert the 20 year totals into annual values.

Cost Savings of Improved Preventative Maintenance Strategies

The condition and life of a pavement can be improved with the timely application of appropriate preventative maintenance strategies. This section will examine the cost savings of using chip seals or slurry seals earlier in the life of the pavement, lengthening the time before an overlay is necessary. For purposes of estimating the potential cost savings, it is assumed that a typical overlay lasts twelve years. Using the SHRP research, a preventative maintenance treatment for that typical highway would be applied at seven years, lasting seven years. A second treatment would be applied after 14 years. The second treatment, since it is applied at a lower PSI level would last an additional five years, giving the total time between overlays of 19 years. The 5 and 7 year treatment lives are consistent with the ranges given in the previous section discussing maintenance strategies. This is compared to current practice of applying preventative maintenance treatments later in the pavement life-cycle, at year 10, and extending the pavement life to year 15 before an overlay is necessary. When each preventative maintenance treatment is applied, it is assumed that there is a slight increase in the PSI level of about 0.1.

The same estimates of asphalt highway mileage used in the improved asphalt binder section are used here, with the local functional class mileage excluded. To eliminate any possibility of double counting, the 25 percent of asphalt mileage assumed to have the incorrect binder specifications is also excluded. This leaves 75 percent of the asphalt highway mileage, or 697,713 miles, which is used as the base for making the cost savings estimates in this section.

Table 56 gives the calculated PSI values for each highway type over a 40 year analysis period. A 40 year analysis period was chosen because it is consistent with the asphalt binder calculations and allows enough time to pass that each scenario goes through at least two life cycles.

The same highway type categories from the improved binder calculations and the MicroBENCOST PC computer program were used to make cost savings estimates of the maintenance treatment scenarios. The PSI values in Table 57 were used, along with the overlay costs in Table 61, from the section "Cost Savings of Improved Binder Specifications" and maintenance costs estimated from the range of treatment costs given in the previous section discussing maintenance strategies. Using $0.75/sy cost of a chip seal or a slurry seal, $21,120/mile is used for each maintenance treatment in the freeway and 4-lane divided categories, and $10,560/mile for the 2-lane undivided categories. A 40 year analysis period was used, along with a 5 percent discount rate. Since neither scenario ends a life-cycle at the end of the 40 year analysis period, the overlay costs for the last partial cycle are prorated for the portion of the life remaining in the analysis period. In the case of the current maintenance scenario, the last overlay occurs with 10 years remaining in the analysis period, so 10/12 of the cost is used. In the case of the improved maintenance scenario, the last overlay occurs with 2 years remaining, so 2/12 of the cost is used. No maintenance treatments had to be prorated. In addition, an annual traffic growth rate of 2.1 percent was assumed, consistent with the improved binder calculations.

The results of the analysis for each highway type is given in Table 58. Detailed MicroBENCOST output are given in Appendix D. The agency cost savings consist of increased maintenance costs due to more frequent treatments, more than offset by the fewer number of required overlays. These cost savings are partially offset by some implementation costs. These implementation costs are based upon expert opinion and consist of some additional equipment and additional personnel costs to conduct the tests on the timing of preventative maintenance strategies. The motorist cost savings are broken down into two categories, delay savings and reduction in vehicle operating costs (VOC). As expected the greatest savings are for the higher volume facilities and much lower savings for the low-volume highways. The urban freeway for example would generate more than $275,000 dollars per mile in motorist savings and over $135,000 per mile in agency savings. In contrast the rural 2-lane highway would be about $20,000 in motorist savings and $15,000 in agency savings.

In order to compare the cost savings, it is necessary to convert the total savings per mile in Table 58 to an annual cost savings. This can be done using equivalent uniform annual cost factors. The factor for a uniform series over 40 years using a 5 percent discount rate is 17.16. By dividing each number in Table 58 by 17.16, they can be converted into annual savings. These annual numbers are given in Table 59. The numbers range from $23,968 for an urban freeway to $2,060 for a rural 2-lane undivided highway.

These annual cost savings per mile can then be aggregated using the total asphalt mileage that could potentially benefit from the improved maintenance strategies. As mentioned above, 75 percent of the total asphalt mileage in the U.S. is used to calculate the total savings. The total annual cost savings are given in Table 60. This table shows that a total of about $3.05 billion could be saved annually in the U.S. using the improved maintenance strategies and timing of those strategies. Of this total, about $1.16 billion would represent annual agency savings, and $1.89 billion represents annual motorist savings.

The numbers in Table 60 represent the total potential annual savings if all agencies immediately implemented the improved maintenance strategies. These savings can only be realized with full implementation through all state and local transportation agencies in the U.S. That implementation process is expected to be a slow, gradual process as case studies are tried and improvements made to the existing recommendations. Tables 61, 62, and 63 give estimates of the total estimated benefits over 20 years assuming a slow implementation scenario, a moderate implementation scenario, and a fast implementation scenario. The slow implementation scenario assumes a 25 percent implementation after 20 years, the moderate implementation scenario assumes a 50 percent implementation after 20 years, and the fast implementation scenario assumes a 100 percent implementation occurring after 20 years. These scenarios give a reasonable range for the expected benefits to the improved maintenance strategies as developed in SHRP. The potential cost savings are substantial, even with these very modest implementation scenarios, ranging from $3.36 billion to $12.61 billion over the next twenty years. The savings to agencies alone would range from $1.28 to $4.79 billion in present value dollars.

Table 57. Yearly PSI Values Used for Preventative Maintenance Strategies.

Year	Freeway		4-Lane Divided		2-Lane Undivided	
	Current Maint. Strat.	Improved Maint. Strat.	Current Maint. Strat.	Improved Maint. Strat.	Current Maint. Strat.	Improved Maint Strat
1	4.30	4.30	4.20	4.20	4.00	4.00
2	4.28	4.28	4.18	4.18	3.98	3.98
3	4.25	4.25	4.14	4.14	3.93	3.93
4	4.19	4.19	4.08	4.08	3.87	3.87
5	4.12	4.12	4.00	4.00	3.77	3.77
6	4.02	4.02	3.89	3.89	3.65	3.65
7	3.89	3.89	3.76	3.76	3.49	3.49
8	3.73	3.98	3.59	3.85	3.30	3.58
9	3.54	3.95	3.39	3.82	3.07	3.55
10	3.33	3.90	3.15	3.76	2.80	3.49
11	3.42	3.82	3.24	3.67	2.89	3.39
12	3.38	3.69	3.20	3.54	2.85	3.24
13	3.30	3.53	3.12	3.37	2.75	3.05
14	3.18	3.33	2.99	3.15	2.61	2.80
15	3.00	3.42	2.80	3.24	2.40	2.89
16	4.30	3.38	4.20	3.20	4.00	2.85
17	4.28	3.30	4.18	3.12	3.98	2.75
18	4.25	3.18	4.14	2.99	3.93	2.61
19	4.19	3.00	4.08	2.80	3.87	2.40
20	4.12	4.30	4.00	4.20	3.77	4.00
21	4.02	4.28	3.89	4.18	3.65	3.98
22	3.89	4.25	3.76	4.14	3.49	3.93
23	3.73	4.19	3.59	4.08	3.30	3.87
24	3.54	4.12	3.39	4.00	3.07	3.77
25	3.33	4.02	3.15	3.89	2.80	3.65
26	3.42	3.89	3.24	3.76	2.89	3.49
27	3.38	3.98	3.20	3.85	2.85	3.58
28	3.30	3.95	3.12	3.82	2.75	3.55
29	3.18	3.90	2.99	3.76	2.61	3.49
30	3.00	3.82	2.80	3.67	2.40	3.39
31	4.30	3.69	4.20	3.54	4.00	3.24
32	4.28	3.53	4.18	3.37	3.98	3.05
33	4.25	3.33	4.14	3.15	3.93	2.80
34	4.19	3.42	4.08	3.24	3.87	2.89
35	4.12	3.38	4.00	3.20	3.77	2.85
36	4.02	3.30	3.89	3.12	3.65	2.75
37	3.89	3.18	3.76	2.99	3.49	2.61
38	3.73	3.00	3.59	2.80	3.30	2.40
39	3.54	4.30	3.39	4.20	3.07	4.00
40	3.33	4.28	3.15	4.18	2.80	3.98

Table 58. Discounted Cost Savings per Mile over a 40 Year Analysis Period (Thous. $)

	Urban			Rural		
	Freeway	4-Lane Divided	2-Lane Undiv	Freeway	4-Lane Divided	2-Lane Undiv
Agency Cost Savings						
Mnt&Ovrly	136.00	88.00	45.00	65.00	49.00	15.00
Implemen	-0.04	-0.04	-0.04	-0.04	-0.04	-0.04
Total	135.96	87.96	44.96	64.963	48.96	14.96
Motorist Cost Savings						
Delay	-75.69	17.76	58.89	-11.08	6.36	8.71
VOC	351.00	85.00	47.24	117.45	30.15	11.67
Total	275.31	102.76	106.13	106.37	36.51	20.38
Total Cost Savings	411.27	190.72	151.09	171.33	85.47	35.34

Source: Output from MicroBENCOST program.

Table 59. Equivalent Uniform Annual Cost Savings per Mile ($).

	Urban			Rural		
	Freeway	4-Lane Divided	2-Lane Undiv	Freeway	4-Lane Divided	2-Lane Undiv
Agency Cost Savings						
Total	7,924	5,126	2,620	3,786	2,853	872
Motorist Cost Savings						
Delay	-4,411	1,035	3,432	-646	371	508
VOC	20,456	4,954	2,753	6,845	1,757	680
Total	16,045	5,989	6,185	6,199	2,128	1,188
Total Cost Savings	23,968	11,115	8,805	9,985	4,981	2,060

Source: Calculated from Table 56.

Table 60. Total Annual Cost Savings (Million $)

	Urban			Rural			Total
	Frwy	4-Ln Div	2-Ln Undiv	Frwy	4-Ln Div	2-Ln Undiv	
Agency Cost Savings							
Total	99.78	202.73	288.86	90.98	46.55	431.55	1,160.45
Motorist Cost Savings							
Delay	-55.55	40.93	378.35	-15.52	6.05	251.26	605.52
VOC	257.60	195.91	303.50	164.50	28.66	336.64	1,286.82
Total	202.05	236.84	681.86	148.98	34.71	587.90	1,892.34
Total Cost Savings	301.84	439.57	970.71	239.96	81.26	1,019.45	3,052.78

Source: Calculated from Table 58, using 75 percent of total asphalt mileage in Table 63, Cost Savings of Improved Binder Specifications.

Table 61. Total Cost Savings with a Slow Implementation Scenario.

Year	Implementation Rate (Percent)	Discounted Agency Savings (Million $)	Discounted Motorist Savings (Million $)	Total Discounted Savings (Million $)
1	1.0	11.60	18.92	30.53
2	1.3	14.37	23.43	37.80
3	1.8	18.95	30.90	49.84
4	2.4	24.06	39.23	63.29
5	3.1	29.60	48.26	77.86
6	4.0	36.37	59.31	95.68
7	4.9	42.43	69.19	111.62
8	5.9	48.66	79.35	128.00
9	7.1	55.77	90.94	146.70
10	8.3	62.09	101.24	163.33
11	9.6	68.39	111.53	179.92
12	11.0	74.63	121.71	196.34
13	12.5	80.77	131.72	212.49
14	14.0	86.16	140.50	226.65
15	15.7	92.02	150.05	242.07
16	17.4	97.13	158.38	255.51
17	19.2	102.07	166.44	268.51
18	21.0	106.32	173.38	279.70
19	23.0	110.90	180.85	291.75
20	25.0	114.81	187.22	302.02
20-Year Total		1,277.09	2,082.54	3,359.63
Equiv. Ann. Tot.		102.48	167.11	269.59

Source: Calculated from Table 58, using a 5 percent discount rate. Equivalent annual totals are calculated using a factor of 12.4622, to convert the 20 year totals into annual values.

Table 62. Total Cost Savings with a Moderate Implementation Scenario.

Year	Implementation Rate (Percent)	Discounted Agency Savings (Million $)	Discounted Motorist Savings (Million $)	Total Discounted Savings (Million $)
1	1.0	11.60	18.92	30.53
2	1.7	18.79	30.64	49.43
3	2.7	28.42	46.34	74.76
4	3.9	39.10	63.75	102.85
5	5.4	51.55	84.07	135.62
6	7.1	64.56	105.27	169.83
7	9.0	77.93	127.09	205.02
8	11.1	91.54	149.28	240.82
9	13.4	105.25	171.63	276.88
10	15.9	118.94	193.95	312.89
11	18.5	131.80	214.92	346.72
12	21.4	145.20	236.77	381.97
13	24.4	157.67	257.11	414.78
14	27.6	169.85	276.98	446.83
15	30.9	181.11	295.33	476.44
16	34.4	192.02	313.12	505.14
17	38.1	202.55	330.29	532.83
18	41.9	212.14	345.93	558.07
19	45.9	221.33	360.91	582.24
20	50.0	229.61	374.43	604.04
20-Year Total		2,450.94	3,996.74	6,447.69
Equiv. Ann. Tot.		196.67	320.71	517.38

Source: Calculated from Table 58, using a 5 percent discount rate. Equivalent annual totals are calculated using a factor of 12.4622, to convert the 20 year totals into annual values.

Table 63. Total Cost Savings with a Fast Implementation Scenario.

Year	Implementation Rate (Percent)	Discounted Agency Savings (Million $)	Discounted Motorist Savings (Million $)	Total Discounted Savings (Million $)
1	1.0	11.60	18.92	30.53
2	2.4	26.52	43.25	69.78
3	4.3	45.26	73.81	119.07
4	6.8	68.17	111.16	179.32
5	9.8	93.56	152.57	246.13
6	13.3	120.93	197.20	318.13
7	17.1	148.08	241.47	389.54
8	21.4	176.49	287.80	464.28
9	26.0	204.21	333.01	537.22
10	31.0	231.89	378.14	610.03
11	36.4	259.32	422.87	682.19
12	42.2	286.32	466.90	753.23
13	48.3	312.11	508.95	821.05
14	54.7	336.63	548.94	885.57
15	61.5	360.45	587.79	948.25
16	68.6	382.92	624.43	1,007.35
17	76.0	404.03	658.84	1,062.87
18	83.7	423.77	691.04	1,114.82
19	91.7	442.17	721.04	1,163.21
20	100.0	459.23	748.86	1,208.09
20-Year Total		4,793.66	7,817.00	12,610.66
Equiv. Ann. Tot.		384.66	627.26	1,011.91

Source: Calculated from Table 58, using a 5 percent discount rate. Equivalent annual totals are calculated using a factor of 12.4622, to convert the 20 year totals into annual values.

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CHAPTER 5

LIFE-CYCLE EFFECTS OF MAINTENANCE

OBJECTIVES

The United States spends $25 billion annually on pavement maintenance and traffic services for its 4-million-mile highway system (4). This expenditure is about 27 percent of the $90 billion spent each year on our highways.

Despite the large amount of money spent on pavement maintenance and the continued expanded need for highway maintenance, little research and development have been devoted to increase worker productivity and safety.

Objectives of SHRP pavement maintenance research were to develop: 1) maintenance management systems to budget, administer and allocate maintenance resources and 2) equipment, materials and methods that increase efficiency and reduce life-cycle costs.

RESEARCH PROJECTS

The proposed SHRP research on pavement maintenance identified three projects: (2)

5. quantifying pavement maintenance effectiveness;
6. measuring systems and instrumentation for evaluating pavement maintenance effectiveness; and
7. improving materials and equipment for pothole repairs, pavement-surface crack repairs and crack filling.

The results were expected to provide better ways to budget, administer and allocate maintenance resources. Successful implementation of the research will allow additional miles of roadways to be operated at a higher level of service for the driving public.

ROUTINE MAINTENANCE

In the SHRP studies, although only one product related to the application of routine maintenance was identified, “Pavement Repair Materials Guidelines,” it included the results of considerable work. The materials and practices studied included those for pothole repair in asphalt pavements, cracks in asphalt pavements, joint sealing in rigid pavements and partial depth patching for spall repairs in rigid pavements. A series of five reports on the work plus two manuals of practice (one each for asphalt concrete and Portland cement concrete surfaced pavements) were prepared. If the guidelines in these manuals are properly applied, it could have a significant impact on the cost-effectiveness of these four routine maintenance treatments applied to pavements in the United States.

Pavement Repair Guidelines

In the conduct of SHRP Project H-105 and H-106, the project staff completed an extensive investigation of the best methods to seal cracks in asphalt pavements, patch potholes in asphalt pavements, reseal joints in rigid pavements and repair spalls in rigid pavements. As a part of this effort, the project staff developed information from the literature review, advisory group and from agency personnel contacted about when the treatments should be applied, the materials to use, the preparation needed, the application of the treatment and evaluating the treatment. From this information, the project staff developed repair guidelines which were published near the end of the project. These repair guidelines cover:

- sealing cracks in asphalt pavements;
- patching potholes with cold mixes and spray injection;
- resealing joints in rigid pavements; and
- using partial depth patches to repair spalls.

For each of these materials, the guidelines generally address:

- determining the need for the repair;
- selecting materials;
- preparation needed before application; and
- application of the treatment.

The recommendations provided in these guidelines are based on the best available information at the time. The include information to assist selection of the best combination based on the needs of the agency and the experience available.

The exact cost of developing these guidelines is difficult to determine because much of the work was completed during the normal conduct of SHRP Projects H-105 and H-106.

The total cost to adopt these guidelines is difficult to estimate. It would be very inexpensive for each agency to decide to adopt them, but the cost to implement the recommendations would depend on:

- whether the agencies had the equipment needed;
- whether the agencies apply the treatments by in-house forces or by contract; and
- how much modification would be needed to the agencies’ specifications for materials, equipment and application processes.

Those agencies that are currently using good materials and techniques would need little adjustment. Those agencies that are doing little of this type of maintenance work or do not have reasonable specifications for materials, equipment and application will require considerable effort to implement the recommendations.

It would be difficult to determine the benefit of all agencies adopting these guidelines. A few agencies are already using most of these procedures; they provided some of the information included. Most agencies would adopt the procedures and incrementally adopt the recommendations that would improve the performance of their existing maintenance work. Other agencies would apply this maintenance work in place of waiting until the pavement had deteriorated to the point where major rehabilitation would be needed.

Material Recommendations

Near the end of SHRP Project H-106, the project staff completed an evaluation of the performance of the four treatments studied:

- sealing cracks in asphalt pavements;
- patching potholes with cold mixes and spray injection in asphalt pavements;
- resealing joints in rigid pavements; and
- using partial depth patches to repair spalls in rigid pavements.

Since many of these had been in place for less than two years at the time of the last assessment, only preliminary information could be made. The study is continuing as a part of the Long-Term Pavement Performance (LTPP) study, and further information will be forthcoming.

Some of the preliminary information from the study is summarized in the following sections.

Pothole Repair

Only cold mixtures and spray injection patching were evaluated. The use of "permanent repairs" with hot mixed asphalt concrete were not studied. Researchers found:

- both materials and application procedures affect performance;
- the environment in which the patches are placed have an impact on their performance; and
- the right combination of materials and application procedures will allow the application of patches that give reasonable performance, even in winter conditions.

Crack Treatment

Sealant materials and crack preparation were both included in the study. Evaluations showed:

- both materials and preparation influence the performance;
- the environment in which the sealants are placed has an impact on performance; and

- reservoir and recessed preparations perform better than those without reservoirs or recessed areas.

Joint Resealing

Both materials and joint preparation were included in the study. It is apparent from the conclusions that adequate time to differentiate between the sealants had elapsed. The results should be considered very preliminary, and evaluation of the benefits will need to be delayed until more information is available.

Spall Repair

Both materials and preparation methods were included. All of the patch materials were considered rapid setting. Again, the results are very preliminary:

- the patches made with Type III cement were performing as well as those made with more expensive proprietary binders; and
- environment had an impact of performance of the materials, some perform better in one climate than another.

General Conclusions

The environment will have impact on the performance of the treatments. The correct material must be selected for the pavement conditions and environment in which it is used. Preparation has an impact on performance of crack sealing. Application technique has an impact on crack and patch performance.

It is to early at this point to discuss benefits from this study. However, it can be seen that when the information is complete, it will be expected that different materials, preparation and applications will have different performance. They probably will perform differently in different environments. This will lead to the need to select the best (most-effective) combination of materials, preparation and application for each area.

PREVENTATIVE MAINTENANCE

In the SHRP studies, three products were identified related to preventive maintenance. These included:

- Manual on Rating Preventive Maintenance;
- Epoxy-core Test for Void Detection; and
- Specifications for Preventive Maintenance.

The first two of these are specific products that have limited, but important, applications. The final one is a preliminary set of information that is related to the cost-effectiveness of the application of preventive maintenance treatments.

Manual on Rating Preventive Maintenance

Although the materials used in maintenance treatments must be properly selected and the mixture of the components must be properly developed, how well the treatment is applied has a very significant impact on how well the treatment will perform. When maintenance treatments are applied, such as a chip seal, slurry seals, etc., it is often difficult to determine just how well that treatment was applied.

This was recognized in the SHRP studies, and a rating procedure was developed. A series of check lists were developed for the four treatments applied to asphalt pavements (chip seals, crack sealing, slurry seals, and thin overlays) and the two treatments applied to rigid pavements (crack/joint sealing and undersealing) on which the inspector recorded information about application of the treatments. A combination of utility analysis and decision tree theories were used to develop a rating process based on the information collected by the inspector. The results of the inspections by the inspector are placed in a spreadsheet that calculates a number that rates the application from high to low based on how well the treatment was applied. Each item rated is weighted based on the importance of that item to the expected performance of the treatment.

In normal practice, if a single item is out of specifications, the work is stopped until changes are made to bring the item back into specification. However, several items that are near the required limits of what is considered acceptable might be more damaging to expected performance than a single item that is slightly out of required limits. This rating process allows quantification of the treatment application process overall. It is not burdensome, because the inspector has to complete only a check list concerning activities the occur during each day’s activities. The results of these are entered into a spreadsheet at the end of the day, and the rating of the applications process for that day is calculated. This gives a numerical rating of the job over time to show how the work is progressing. By watching this numeric value over time using a control chart approach, it can be determined whether the application process is getting better with time or if it is getting worse. It might be possible to make corrections before the work became unacceptable.

Very little money was spent on this product directly. During the conduct of Project H-101, the project team developed check lists for the inspectors who would observe the applications of the treatments. This information was placed in the SHRP database as a part of the H-101 study. The rating system was developed over a few months by the developers with the assistance of a graduate student, and no more than $5000 could be attributed directly to the development of the rating procedure; most of the related funds were spent on developing the check lists which were needed with or without the rating procedure. Engineers in Montana have tried the process and feel that it is beneficial.

It will be difficult to estimate the cost savings based on the implementation of this product because there will not be a dramatic change in activities. It will cost the adopting agency some time and effort to develop the needed checklists, the weighting factors and spreadsheets for calculating the rating. This will be a minimal amount of initial effort, and it will have to be followed by a continued process of reviewing and adapting the checklists, weighting factors and spreadsheets. It will have little effect on the effort of the inspectors in the field, unless there currently are no inspectors. The inspectors have to complete only the check lists while conducting their normal activities. If the checklist are paper in form, the results will have to be entered into a computerized spreadsheet by clerical staff. If the date is entered into a notebook or clipboard computer by the inspector, less data handling will be required.

The amount of savings will depend on how well the agency is currently controlling their maintenance work. If this rating of treatment applications were applied to normal maintenance treatment applications, those responsible would be better able to determine if the treatments were being applied appropriately or if there were significant changes in treatment application over time. By tracking the overall application rating, the agency and applying agency might be able to identify problems as they start to develop and keep them from becoming severe enough to warrant work stoppage. It might also help the agencies to identify areas that need to be better controlled to ensure that the overall activities were likely to provide the desired level of service rather than keying only on the items that are out of compliance, after they have reached that stage. Since treatment application is so critical to the useful life of maintenance treatments, this would help ensure that the maintenance treatments were being applied as needed to give the desired life. This would result in longer lives for the maintenance treatments applied. Any slight increase in life would give a huge cost-benefit ratio since so little was spent on the development. The amount of effort that the agencies put into this would depend on how well they are currently managing maintenance treatment application. Those who are doing the best would require less effort to implement this process, but they would also have a smaller savings. Those who are doing the least to manage their maintenance treatment applications would probably require the most effort to implement it, but their savings due to improved management could be quite substantial.

Epoxy Core Test

The epoxy core test was developed as a part of SHRP Project H-101. Since one of the treatments applied to concrete pavements studied was undersealing, there was a need to verify the presence of voids under concrete pavements. Ground penetrating radar, deflection testing, sounding and other techniques had been used to try to locate the presence of voids. However, short of removing a slab after testing, there was no direct method to verify that these other techniques were accurately locating voids under the concrete pavements.

In the epoxy core test, a small hole is drilled through a concrete pavement. A colored, low viscosity epoxy is poured into the hole until it stops flowing, and it is allowed to harden. A core drill is then used to cut through the slab through the epoxy hole. If the core is taken before the slab is undersealed, the presence and depth of the void can be determined from the thickness of the epoxy; in addition, if the slab was raised by the undersealing, this can be determined by the thickness of the grout below the epoxy.

The epoxy core test was developed as a part of the H-101 study and the direct costs are difficult to determine, but it is estimated that the cost directly attributable to the epoxy core test was probably no more than $30,000. This included some verification work that was also a part of the verification of other equipment to locate voids under concrete pavements.

This test has been used by several agencies since it was developed, including the Texas Transportation Institute. If no equipment is available, it would cost $3000 to $5000 to gather the equipment needed to complete the test. If the coring and power supply equipment is available, then it would cost the agency about $500 to gather the equipment to complete the test. It takes the time on the pavement surface required to drill the hole and put in the epoxy, about fifteen minutes. After the epoxy has hardened, either before or after undersealing, the four-inch core must be taken and the core hole filled. This normally requires about another fifteen minutes. The overall cost is equivalent to about two core holes for each test, plus the traffic control. If the tests are conducted at the same time the non-destructive testing is being completed for the initial hole and during the treatment process for the core retrieval, then there would be no additional traffic control cost or traffic disruption.

It is difficult to determine the expected savings directly attributable to the development of the epoxy core test. This test is not expected to be used as a routine test to test every slab suspected of having a void nor to test every slab that has been undersealed. The primary use of this test is to verify that currently available, or future developed, non-destructive testing equipment used to locate void under concrete pavement slabs is accurately locating voids and to verify that the thickness of voids found by this equipment is accurate. It can also be used to verify that equipment used to monitor slab movement is working to ensure that slabs are not lifted. However, it is apparent that this is the first fairly simple test available to make these verifications, and it could easily be used at each undersealing site, or at each evaluation by non-destructive testing equipment. If it is used to verify the accuracy of the non-destructive testing equipment, it will lead to better identification of voids before they become so large that they can be repaired before they require major reconstruction to repair them. It would also ensure that only slabs with voids would be prepared for undersealing and have grout pumped under them. If it is used to verify the accuracy of slab lift detection equipment, it would help ensure that slabs are not lifted which often leads to secondary cracking of the slabs due to change in support due to the lifting. The value of this is difficult to estimate.

Specifications for Preventive Maintenance

One of the products listed is specification for preventive maintenance treatments. These specifications were developed using the best possible information from state highway agencies, the industry and academia. They were developed so that they could be used in the application of the SPS-3 and SPS-4 treatments to ensure that best possible chance of successfully applying the treatments to be studied over a long period of time.

These materials and method type specifications would have to be slightly modified for use in individual agencies, because each agency has different materials available. However, that modification would be minor. The following describes some of the problems that were encountered during treatment application that were addressed in the specifications.

Lack of Detailed Specifications

Some of the treatments have traditionally been applied primarily by agency forces rather than by contract. In those agencies, the specifications for those treatments were not well developed. For those agencies that had traditionally contracted the application of the treatments, the specifications were well developed.

Chip Spreaders

Few of the state DOT agencies that we worked with during the H-101 application were calibrating the chip spreaders for transverse distribution of the cover stones. By applying a simple calibration process developed at the University of Nevada-Reno, the aggregate will be more evenly distributed across the pavement service leading to a longer life for the chip seals applied by the agencies. The agencies should require that the chip spreaders be calibrated prior to use and at a reasonable interval thereafter.

Asphalt Distributors

Fewer than one half of the state DOT agencies that we worked with during the H-101 application were calibrating the asphalt distributors using the ASTM D 2995 standard practice. The procedure is extremely time consuming and difficult to complete accurately. This is in part because this calibration method was not developed for the asphalt cements that we used. Although the cost of calibration may be relatively large compared to calibration costs for chip spreaders, it is critical that the asphalt distributors be accurately calibrated for both the longitudinal and transverse distribution. Accurate application of the binder will lead to longer life for the chip seals applied by the agencies with fewer failures and reduced service. The agencies should require that the asphalt distributors be calibrated prior to use and at a reasonable interval thereafter.

A simpler, less time consuming, and less costly method of calibration needs to be developed to make it simpler to complete this calibration.

Emulsion Specifications

The emulsion specifications do not define the properties of the residual asphalt cement very well. The primary measure is penetration, and the range allowed is quite wide. The specifications required a specific grade of asphalt cement be the base stock prior to emulsification.

This would reduce the variability in performance to the variability of the asphalt binder in emulsions.

Summary

These are a few of the key items encountered in the H-101 study that indicate a need for improved specifications in may of the agencies.

It would be impossible to determine the exact funds spent on developing these specifications because they were developed as a part of the overall project and were not developed as a separate entity. It is estimated that no more than $20,000 was devoted to this development, and this included review and adjustments in several meetings.

It would also be impossible to determine the exact funds that would be required by agencies to modify their existing specifications based on those developed in the SHRP H-101 study. Each agency has some type of specification. The developers used a group of experts to take the best idea from each agency and combine them into a single specification. These were considered products because they were thought to be the best possible specifications to use as guide specifications by agencies interested in applying these treatments. Most agencies are continuously striving to develop the best specifications possible for their climate, materials, and work forces. Some agencies have treatment specifications that are similar to these, and they were used as a pattern from which these were developed. Other agencies have specifications that could use considerable improvement. It is not known what percent of the agencies use specifications that need considerable improvement, and the costs to an agency would be incremental and considered as a part of their normal activities.

The savings due to the use of these specifications would also be difficult to determine. Those agencies that already have treatment specifications that are similar to these would experience little costs to adopt them but also experience little increase in benefit because their existing specifications are currently adequate. Those agencies that have inadequate or problem specifications would experience the most cost to implement them but also the greatest benefit. In general, it is expected that those agencies that did adopt improved specifications would experience improved performance of their maintenance treatments resulting in longer lives of the treatments for very little increase in contracted maintenance costs. However, it is not known what percent of the agencies would experience dramatic improvement. It is expected that many agencies would show some improvement, but that improvement would be incremental. However, since considerable funds are spent on contracted pavement maintenance, the increase in life for little investment in cost could have a dramatic impact on cost-effectiveness.

Preventive Maintenance Summary

The costs incurred to develop these products were minimal. The costs to implement them is also low, although difficult to quantify because their adoption should be a part of an agency’s normal process of continuous improvement that occurs incrementally rather than dramatically. The monetary benefits of adopting these products are also difficult to quantify, partly because of incremental adoption and partly because some agencies will benefit much more that others. It is apparent that these products can provide significant incremental improvements in the lives of the treatments in some agencies. At this time it is not known which agencies would benefit most from adopting them because some agencies already use similar procedures.

EQUIPMENT AUTOMATION

Four devices were evaluated to help automate some part of maintenance in the SHRP studies. Two of these were directed at automating actual maintenance activities; the crack sealing and the patching devices. Two were directed at collecting information to determine when preventive maintenance treatments were needed; the ground penetrating radar and the seismic pavement analyzer.

Crack Sealing Automation

The purpose of this device was to automate crack sealing. The general concept was to use cameras and vision analysis to locate the cracks. The crack preparation and sealing equipment would be on a frame. The information from the cameras and vision analysis would direct the crack preparation and sealing process. This would reduce the number of workers required to seal cracks, and it would improve safety by removing workers from the traffic lanes.

Although there was significant progress through the support provided by SHRP, the equipment was not fully operating at the end of the contract. It was hoped that the developers and CALTRANS would continue development to the point that the equipment, or some version of it, was fully operational.

Robotic Pothole Patching Vehicle

The purpose of this device was to automate pothole patching to the point where a truck would approach the pothole, cameras would take a picture of the pothole, vision analysis would be used to determine what needed to be done, and a computer would direct the equipment to prepare, fill and finish the pothole. This would reduce the number of workers needed to repair potholes, and it would improve safety by removing workers from the traffic lanes.

Although there was improvement in the operation of a pothole patching device, the process was changed to a manually controlled robotic system instead of a fully computer controlled device before the end of the project. At the end of the project, the device was capable of filling potholes, but it was similar to others available on the commercial market. It was hoped that the developers and industry would continue development in the future on a fully automated device.

Radar for Pavement Subsurface Condition

The purpose of this device was to improve both the equipment and the analysis tools used to determine the subsurface condition of pavements. The goal was to be able to identify areas of the pavement that might develop damage in the future so that preventive maintenance could be applied to prevent or retard the development of that damage.

It was found that new antennae were needed to get better resolution of the damage developing in the pavement compared to the antennae currently being used. Considerable effort was placed into developing these new antennae that would have smaller waves to get better resolution of the damage developing within or below the pavement. A new set of analysis algorithms was developed and tested that allow a more quantitative interpretation of the radar signals. Most of the interpretation to this point had been by manually viewing the color coded return waves to identify anomalies. These were then interpreted by experts to mean certain things based on their experience. The new algorithm quantified the results in a way that allows a more accurate interpretation of the meaning.

Seismic Pavement Analyzer

This device uses seimic principles to measure the properties of the existing pavement. Seimic analysis has been available for a considerable period of time; however, it has not been used for routine pavement testing. The hope was that this device could be used for routine pavement testing to identify areas of pavements that are starting to experience damage so that less expensive preventive maintenance treatments could be applied before the pavement deteriorated to the point that more expensive rehabilitation treatments were needed.

One of the reasons that seismic analysis has not been used significantly in routine pavement testing is that the tests required that accelerometers be fastened to the surface, a test conducted, the accelerometers be moved, another test conducted, etc. This required considerable time and effort to conduct a single test. The travel lane has to be closed so that the tests can be conducted. The results of most seimic analysis could be interpreted only by specialists who had graduate level education in the use of seimic analysis of geotechnical material.

In this study, the seimic test equipment was mounted on a trailer that could be towed along the pavement. The vehicle would stop and the test would be conducted. After a short period of time, the vehicle could move to another site to conduct another test. The test time and resulting traffic interruption were similar to that required by an Falling Weight Deflectometer (FWD). A set of interpretation software was developed that gives simple information about the condition of the pavement. It appears that the information may be more beneficial for finding pavements that have deteriorated to the point that major rehabilitation is needed and identifying the extent of that deterioration than for identifying where deterioration may occur in the future. However, this is a significant development.

At the end of the project, a prototype of the equipment was available. It appears that it is ready for complete field testing. It is hoped that the developers will continue with the field testing, and that agencies will be interested in using this device as another method of pavement evaluation to determine what type of treatment is needed and the extent of the area of the pavement that needs treatment.

Predicting Performance

The current plans call for adjustment to the AASHTO design equations for predicting performance. However, the AASHTO design equations are not capable of showing the effect of preventive maintenance as they are currently presented nor based on the initial suggested modifications based on SHRP LTPP data (1). The AASHTO design equations predict performance only as a function of number of 18 kip equivalent single axle loads (ESALs). Figure 1 shows the expected performance for any given number of ESALs, say 10 million, whether those 10 million ESALs are applied over 10 years or 50 years. In either case. The preventive maintenance treatments will not significantly increase the fatigue life of the pavement because they do not significantly increase the structural section (and the resulting structural number) of pavement. However, from experience, we know that the pavement designed for 10 million ESALs applied over 50 years will not be able to support those 10 million ESALs without the application of additional treatments during that 50 year period.

The current AASHTO design equations are capable of determining only the structural sections needed. They are not capable of determining the preventive maintenance treatments needed. To achieve this, the equations will need to be modified to include the effects of time and environment.

OTHER PRODUCT IN THE DEVELOPMENT

At the end of H-101, the study of the treatment performance was transferred to the LTPP study as SPS-3 and SPS-4. Some of the findings indicate the type of benefits that are already coming out of the project and others indicate what might be expected in the future.

Lessons Learned of Significant Impact During H-101

During Construction

During the application of the treatments, several lessons were learned that could have a significant impact on the lives of the treatments while adding little to the cost of the treatment.

Initial Failures

Four preventive maintenance treatments were placed on asphalt concrete surfaces, chip seals, crack sealing, slurry seals, and thin overlays. One slurry seal had a significant failure during construction because of equipment problems. No immediate failures were noted for the crack sealing and the thin overlays. Several chip seal had immediate failures. Of the four treatments, immediate failures are more likely to occur in chip seals for a number of reasons, part of which will be described below. If failures cannot be accepted, then much better control of the application and materials will have to be maintained than is normally present during application. Otherwise, one of the other treatments should be selected.

Application to Porous Friction Course Surfaces

During two of the H-101 applications, the chip seals were applied to surfaces that were thought to be hot mixed asphalt concrete at the time of selection. However, the surfaces were actually older porous friction courses that appeared to have flushed. When the emulsified asphalt cement was applied, the distributor could not apply enough to initially bind the cover aggregate. On these types of surfaces, a trial application needs to be completed. In most cases, a tack coat (or fog application) will need to be applied prior to the application of the binder. By using this approach, there will be fewer chip seals applied that lose the cover aggregate resulting in fewer failures.

During Early Years of Observation

During the early years of observation of performance, several lessons were learned that should enhance the cost-effectiveness of treatments.

Hydro-Genesis

At a few sites, the treated sections failed more quickly than the untreated sections. Initial investigations showed that these sites were primarily in dry climatic zones and that the aggregates in the original hot mixed asphalt concrete was subject to stripping. During the normal performance, moisture (probably in vapor form) is drawn to the surface by higher temperatures. It migrates through the hot mixed asphalt concrete surface, but part of it is trapped within the asphalt concrete in water form when the surface cools at night causing the vapor to condense into a liquid. This will eventually cause the asphalt concrete to strip if necessary traffic loads are present. When the chip seals, slurry seals and thin overlays were placed on this mixture, they retarded the escape of the moisture through the surface, leading to more moisture in the asphalt mixture and to more rapid development of stripping.

In the past, it was understood that a thorough analysis of the project must be completed prior to application of a rehabilitation. However, it was believed that preventive maintenance treatments could be applied with a minimal analysis. These problems show that, particularly in dry climates, an analysis of stripping potential must be completed prior to application of preventive maintenance treatments, as well as the application of rehabilitation treatments. By applying these principles, fewer treatments that enhance the effects of stripping will be applied.

Selecting the Correct Treatment

It is apparent from the early observations that different treatments perform better on pavements with different initial conditions. If cracking is a primary distress, slurry seals will not provide much of a life extension; however, if weathering and raveling are the primary distress, slurry seals will provide a reasonable life with fewer immediate failures that chip seals at about the same cost. If thermal cracking is a primary distress, sealing the cracks with appropriate preparation and continued maintenance will provide a reasonable life without requiring that the entire surface be covered. If a small or moderate amount of fatigue cracking is present on this surfaced asphalt concrete pavements, chip seals will give reasonable life extension. Thin overlays seem to work relatively well in most of the above applications. None of the treatments will give significant life extensions if the pavement has significant fatigue cracking, especially if much of the structural strength of the pavement is in the asphalt concrete layer.

Crack sealing appears to give better life extension in colder climates applied to thermal cracking. Chip seals and slurry seals both appear to give better life extensions in warmer climates. Thin overlays will work in either climate; however, they appear to have a better life extension ratio over slurry seals and chips seals in colder climates.

The crack sealed sections with the recessed band-aid application configuration appear to be performing better than the other application configurations. More work needs to be completed to determine the best preparation configuration for different climates.

The discussions above lead to the conclusion that the different treatments should not be interchanged for each other, but rather they should be applied to pavements in the appropriate condition for the specific treatment. A selection process is needed for these treatments so that those most appropriate are selected for the specific condition of the pavement being treated. This process should also consider the climate in which the pavement is located. By selecting the appropriate treatment for the current condition of the pavement, the best life extension for the treatment will be achieved.

Continued Maintenance

In the H-101 treatments, the crack sealing sections were supposed to be kept sealed by the responsible agencies. Those sections that have not been maintained by repeated application of crack sealing as the sealants failed are deteriorating more quickly than those that have been resealed. If the cracks are routed, sealed, but not maintained, the routed areas may deteriorate more quickly than cracks that were not routed. For the crack sealing to be effective, the sealant must be replaced as it fails. If the crack sealant is not going to be maintained, it may be better not to rout the crack.

General Conclusions

- All four of the treatments can be placed on pavements in all of the climatic zones and on pavements at all levels of traffic.
- Individual sites need to be investigated prior to the application of the treatments. This will cost more than applying the treatment without evaluation, but it will prevent the treatment from accelerating a developing damage that cannot be treated with the treatment. The amount of this investigation will vary from region to region.
- Currently, chip seals have a higher rate of initial failure than the other treatments, but that could be alleviated by proper construction.
- Each treatment addresses different problems, and probably will be more cost-effective when applied to pavements with different problems at different states of deterioration.
- Crack sealing must be resealed on a continuing basis for the treatment to be effective. If the crack is prepared by routing, that crack may deteriorate more quickly than an unprepared crack if the sealant is not maintained.

Treatment Costs

The following cost information is based on discussions with both DOT and contractors. The cost will vary from region to region and even within region based on transportation costs of raw and combined materials. All costs are in terms of dollars per square yard (except for the cost of crack sealing that are in dollars per linear foot), which were the areas used in the preventive maintenance treatments for SHRP.

Chip seals	0.70 to 0.80 ($/sy)
Slurry seals	0.60 to 0.75 ($/sy)
Thin overlays	1.50 to 2.40 ($/sy)
Crack sealing	0.50 to 1.50 ($/lf)

Similar treatments may be substituted.

Rubber chip seals	0.95 to 1.10 ($/sy)
Micro-Surfacing	1.20 to 2.20 ($/sy)

Treatment Lives

The lives of the treatments have been much more difficult to determine at this time. Although several agencies were contracted, solid information on individual treatments was not available from any of the agencies. Those agencies with some data basically have gross data based preventive maintenance without specific information on individual treatments. However, the following ranges of lives are considered reasonable and should be identified as reasonable lives that are yet to be verified by the SHRP SPS-3 studies.

Chip seals	4 to 7 years
Slurry seals	3 to 5 years
Thin overlays	5 to 9 years
Crack sealing	0 to 5 years

These lives are pretty gross, and they are the lives from the time of treatment until the pavement returns back to the condition at time of treatment. If the treatment is placed early in life, then the greater number is more appropriate. If the treatment is placed when the condition of the pavement is poorer, then the lower life would be expected from the treatment. The region of the country will also have an impact. Seals and thin overlays have less life in colder areas. Crack sealing treatments, applied properly, and maintained, will have higher lives. Crack sealing can be repeated periodically and continue to give additional life.

Cost Savings of Improved Preventative Maintenance Strategies

The condition and life of a pavement can be improved with the timely application of appropriate preventative maintenance strategies. This section will examine the cost savings of using chip seals or slurry seals earlier in the life of the pavement, lengthening the time before an overlay is necessary. For purposes of estimating the potential cost savings, it is assumed that a typical overlay lasts twelve years. Using the SHRP research, a preventative maintenance treatment for that typical highway would be applied at seven years, lasting seven years. A second treatment would be applied after 14 years. The second treatment, since it is applied at a lower PSI level would last an additional five years, giving the total time between overlays of 19 years. The five and seven year treatment lives are consistent with the ranges given in the previous section discussing maintenance strategies. This is compared to current practice of applying preventative maintenance treatments later in the pavement life-cycle, at year 10, and extending the pavement life to year 15 before an overlay is necessary. When each preventative maintenance treatment is applied, it is assumed that there is a slight increase in the PSI level of about 0.1.

The same estimates of asphalt highway mileage used in the improved asphalt binder section are used here, with the local functional class mileage excluded. To eliminate any possibility of double counting, the 25 percent of asphalt mileage assumed to have the incorrect binder specifications is also excluded. This leaves 75 percent of the asphalt highway mileage, 697,713 miles, which are used as the base for making the cost savings estimates in this section.

Table 64 gives the calculated PSI values for each highway type over a 40 year analysis period. A 40 year analysis period was chosen because it is consistent with the asphalt binder calculations and allows enough time to pass that each scenario goes through at least two life cycles.

The same highway type categories from the improved binder calculations and the MicroBENCOST PC computer program were used to make cost savings estimates of the maintenance treatment scenarios. The PSI values in Table 64 were used, along with the overlay costs in Table 67, from the section "Cost Savings of Improved Binder Specifications" and maintenance costs estimated from the range of treatment costs given in the previous section discussing maintenance strategies. Using $0.75/sy cost of a chip seal or a slurry seal, $21,120/mile is used for each maintenance treatment in the freeway and 4-lane divided categories, and $10,560/mile for the 2-lane undivided categories. A 40 year analysis period was used, along with a 5 percent discount rate. Since neither scenario ends a life-cycle at the end of the 40 year analysis period, the overlay costs for the last partial cycle are prorated for the portion of the life remaining in the analysis period. In the case of the current maintenance scenario, the last overlay occurs with 10 years remaining in the analysis period, so 10/12 of the cost is used. In the case of the improved maintenance scenario, the last overlay occurs with 2 years remaining, so 2/12 of the cost is used. No maintenance treatments had to be prorated. In addition an annual traffic growth rate of 2.1 percent was assumed, consistent with the improved binder calculations.

The results of the analysis for each highway type is given in Table 64. Detailed MicroBENCOST outputs are given in Appendix D. The agency cost savings consist of increased maintenance costs due to more frequent treatments, that is more than offset by the fewer number of required overlays. These cost savings are partially offset by some implementation costs. These implementation costs are based upon expert opinion and consist of some additional equipment and additional personnel costs to conduct the tests on the timing of preventative maintenance strategies. The motorist cost savings are broken down into two categories, delay savings and reduction in vehicle operating costs (VOC). As expected, the greatest savings are for the higher volume facilities and much lower savings for the low-volume highways. The urban freeway, for example, would generate more than $275,000 dollars per mile in motorist savings and over $135,000 per mile in agency savings. In contrast the rural 2-lane highway would be about $20,000 in motorist savings and $15,000 in agency savings.

Table 64. Yearly PSI Values Used for Preventative Maintenance Strategies.

Year	Freeway		4-Lane Divided		2-Lane Undivided	
	Current Maint. Strat.	Improved Maint. Strat.	Current Maint. Strat.	Improved Maint. Strat.	Current Maint. Strat.	Improved Maint Strat
1	4.30	4.30	4.20	4.20	4.00	4.00
2	4.28	4.28	4.18	4.18	3.98	3.98
3	4.25	4.25	4.14	4.14	3.93	3.93
4	4.19	4.19	4.08	4.08	3.87	3.87
5	4.12	4.12	4.00	4.00	3.77	3.77
6	4.02	4.02	3.89	3.89	3.65	3.65
7	3.89	3.89	3.76	3.76	3.49	3.49
8	3.73	3.98	3.59	3.85	3.30	3.58
9	3.54	3.95	3.39	3.82	3.07	3.55
10	3.33	3.90	3.15	3.76	2.80	3.49
11	3.42	3.82	3.24	3.67	2.89	3.39
12	3.38	3.69	3.20	3.54	2.85	3.24
13	3.30	3.53	3.12	3.37	2.75	3.05
14	3.18	3.33	2.99	3.15	2.61	2.80
15	3.00	3.42	2.80	3.24	2.40	2.89
16	4.30	3.38	4.20	3.20	4.00	2.85
17	4.28	3.30	4.18	3.12	3.98	2.75
18	4.25	3.18	4.14	2.99	3.93	2.61
19	4.19	3.00	4.08	2.80	3.87	2.40
20	4.12	4.30	4.00	4.20	3.77	4.00
21	4.02	4.28	3.89	4.18	3.65	3.98
22	3.89	4.25	3.76	4.14	3.49	3.93
23	3.73	4.19	3.59	4.08	3.30	3.87
24	3.54	4.12	3.39	4.00	3.07	3.77
25	3.33	4.02	3.15	3.89	2.80	3.65
26	3.42	3.89	3.24	3.76	2.89	3.49
27	3.38	3.98	3.20	3.85	2.85	3.58
28	3.30	3.95	3.12	3.82	2.75	3.55
29	3.18	3.90	2.99	3.76	2.61	3.49
30	3.00	3.82	2.80	3.67	2.40	3.39
31	4.30	3.69	4.20	3.54	4.00	3.24
32	4.28	3.53	4.18	3.37	3.98	3.05
33	4.25	3.33	4.14	3.15	3.93	2.80
34	4.19	3.42	4.08	3.24	3.87	2.89
35	4.12	3.38	4.00	3.20	3.77	2.85
36	4.02	3.30	3.89	3.12	3.65	2.75
37	3.89	3.18	3.76	2.99	3.49	2.61
38	3.73	3.00	3.59	2.80	3.30	2.40
39	3.54	4.30	3.39	4.20	3.07	4.00
40	3.33	4.28	3.15	4.18	2.80	3.98

Table 65. Discounted Cost Savings per Mile over a 40 Year Analysis Period (Thous. $)

	Urban			Rural		
	Freeway	4-Lane Divided	2-Lane Undiv	Freeway	4-Lane Divided	2-Lane Undiv
Agency Cost Savings						
Mnt&Ovrly	136.00	88.00	45.00	65.00	49.00	15.00
Implemen	-0.04	-0.04	-0.04	-0.04	-0.04	-0.04
Total	135.96	87.96	44.96	64.963	48.96	14.96
Motorist Cost Savings						
Delay	-75.69	17.76	58.89	-11.08	6.36	8.71
VOC	351.00	85.00	47.24	117.45	30.15	11.67
Total	275.31	102.76	106.13	106.37	36.51	20.38
Total Cost Savings	411.27	190.72	151.09	171.33	85.47	35.34

Source: Output from MicroBENCOST program.

Table 66. Equivalent Uniform Annual Cost Savings per Mile ($).

	Urban			Rural		
	Freeway	4-Lane Divided	2-Lane Undiv	Freeway	4-Lane Divided	2-Lane Undiv
Agency Cost Savings						
Total	7,924	5,126	2,620	3,786	2,853	872
Motorist Cost Savings						
Delay	-4,411	1,035	3,432	-646	371	508
VOC	20,456	4,954	2,753	6,845	1,757	680
Total	16,045	5,989	6,185	6,199	2,128	1,188
Total Cost Savings	23,968	11,115	8,805	9,985	4,981	2,060

Source: Calculated from Table 64.

In order to compare the cost savings, it is necessary to convert the total savings per mile in Table 65 to an annual cost savings. This can be done using equivalent uniform annual cost factors. The factor for a uniform series over 40 years using a 5 percent discount rate is 17.16. By dividing each number in Table 65 by 17.16, they can be converted into annual savings. These annual numbers are given in Table 65. The numbers range from $23,968 for an urban freeway to $2,060 for a rural 2-lane undivided highway.

These annual cost savings per mile can then be aggregated using the total asphalt mileage that could potentially benefit from the improved maintenance strategies. As mentioned above 75 percent of the total asphalt mileage in the U.S. is used to calculate the total savings. The total annual cost savings are given in Table 66. This table shows that a total of about $3.05 billion could be saved annually in the U.S. using the improved maintenance strategies and timing of those strategies. Of this total, about $1.16 billion would represent annual agency savings, and $1.89 billion represents annual motorist savings.

The numbers in Table 66 represent the total potential annual savings if all agencies immediately implemented the improved maintenance strategies. These savings can only be realized with full implementation through all state and local transportation agencies in the U.S. That implementation process is expected to be a slow, gradual process as case studies are tried and improvements made to the existing recommendations. Tables 67, 68, and 69 give estimates of the total estimated benefits over 20 years assuming a slow implementation scenario, a moderate implementation scenario, and a fast implementation scenario. The slow implementation scenario assumes a 25 percent implementation after 20 years, the moderate implementation scenario assumes a 50 percent implementation after 20 years, and the fast implementation scenario assumes a 100 percent implementation occurring after 20 years. These scenarios give a reasonable range for the expected benefits to the improved maintenance strategies as developed in SHRP. The potential cost savings are substantial, even with these very modest implementation scenarios, ranging from $3.36 billion to $12.61 billion over the next 20 years. The savings to agencies alone would range from $1.28 to $4.79 billion in present value dollars.

Table 67. Total Annual Cost Savings (Million $).

	Urban			Rural			Total
	Frwy	4-Ln Div	2-Ln Undiv	Frwy	4-Ln Div	2-Ln Undiv	
Agency Cost Savings Total	99.78	202.73	288.86	90.98	46.55	431.55	1,160.45
Motorist Cost Savings							
Delay	-55.55	40.93	378.35	-15.52	6.05	251.26	605.52
VOC	257.60	195.91	303.50	164.50	28.66	336.64	1,286.82
Total	202.05	236.84	681.86	148.98	34.71	587.90	1,892.34
Total Cost Savings	301.84	439.57	970.71	239.96	81.26	1,019.45	3,052.78

Source: Calculated from Table 66, using 75 percent of total asphalt mileage in Table 71, Cost Savings of Improved Binder Specifications.

Table 68. Total Cost Savings with a Slow Implementation Scenario.

Year	Implementation Rate (Percent)	Discounted Agency Savings (Million $)	Discounted Motorist Savings (Million $)	Total Discounted Savings (Million $)
1	1.0	11.60	18.92	30.53
2	1.3	14.37	23.43	37.80
3	1.8	18.95	30.90	49.84
4	2.4	24.06	39.23	63.29
5	3.1	29.60	48.26	77.86
6	4.0	36.37	59.31	95.68
7	4.9	42.43	69.19	111.62
8	5.9	48.66	79.35	128.00
9	7.1	55.77	90.94	146.70
10	8.3	62.09	101.24	163.33
11	9.6	68.39	111.53	179.92
12	11.0	74.63	121.71	196.34
13	12.5	80.77	131.72	212.49
14	14.0	86.16	140.50	226.65
15	15.7	92.02	150.05	242.07
16	17.4	97.13	158.38	255.51
17	19.2	102.07	166.44	268.51
18	21.0	106.32	173.38	279.70
19	23.0	110.90	180.85	291.75
20	25.0	114.81	187.22	302.02
20-Year Total		1,277.09	2,082.54	3,359.63
Equiv. Ann. Tot.		102.48	167.11	269.59

Source: Calculated from Table 67, using a 5 percent discount rate. Equivalent annual totals are calculated using a factor of 12.4622, to convert the 20 year totals into annual values.

Table 69. Total Cost Savings with a Moderate Implementation Scenario.

Year	Implementation Rate (Percent)	Discounted Agency Savings (Million $)	Discounted Motorist Savings (Million $)	Total Discounted Savings (Million $)
1	1.0	11.60	18.92	30.53
2	1.7	18.79	30.64	49.43
3	2.7	28.42	46.34	74.76
4	3.9	39.10	63.75	102.85
5	5.4	51.55	84.07	135.62
6	7.1	64.56	105.27	169.83
7	9.0	77.93	127.09	205.02
8	11.1	91.54	149.28	240.82
9	13.4	105.25	171.63	276.88
10	15.9	118.94	193.95	312.89
11	18.5	131.80	214.92	346.72
12	21.4	145.20	236.77	381.97
13	24.4	157.67	257.11	414.78
14	27.6	169.85	276.98	446.83
15	30.9	181.11	295.33	476.44
16	34.4	192.02	313.12	505.14
17	38.1	202.55	330.29	532.83
18	41.9	212.14	345.93	558.07
19	45.9	221.33	360.91	582.24
20	50.0	229.61	374.43	604.04
20-Year Total		2,450.94	3,996.74	6,447.69
Equiv. Ann. Tot.		196.67	320.71	517.38

Source: Calculated from Table 67, using a 5 percent discount rate. Equivalent annual totals are calculated using a factor of 12.4622, to convert the 20 year totals into annual values.

Table 70. Total Cost Savings with a Fast Implementation Scenario.

Year	Implementation Rate (Percent)	Discounted Agency Savings (Million $)	Discounted Motorist Savings (Million $)	Total Discounted Savings (Million $)
1	1.0	11.60	18.92	30.53
2	2.4	26.52	43.25	69.78
3	4.3	45.26	73.81	119.07
4	6.8	68.17	111.16	179.32
5	9.8	93.56	152.57	246.13
6	13.3	120.93	197.20	318.13
7	17.1	148.08	241.47	389.54
8	21.4	176.49	287.80	464.28
9	26.0	204.21	333.01	537.22
10	31.0	231.89	378.14	610.03
11	36.4	259.32	422.87	682.19
12	42.2	286.32	466.90	753.23
13	48.3	312.11	508.95	821.05
14	54.7	336.63	548.94	885.57
15	61.5	360.45	587.79	948.25
16	68.6	382.92	624.43	1,007.35
17	76.0	404.03	658.84	1,062.87
18	83.7	423.77	691.04	1,114.82
19	91.7	442.17	721.04	1,163.21
20	100.0	459.23	748.86	1,208.09
20-Year Total		4,793.66	7,817.00	12,610.66
Equiv. Ann. Tot.		384.66	627.26	1,011.91

Source: Calculated from Table 67, using a 5 percent discount rate. Equivalent annual totals are calculated using a factor of 12.4622, to convert the 20 year totals into annual values.

Calculation of Agency Savings from Improved Pothole Patching

Annual pothole patching expenditures by state transportation agencies in the United States are estimated at about $300 to $400 million dollars. Spending by local governments also is considerable. SHRP research indicates that these expenditures can be reduced considerably.

SHRP research covers several aspects of pothole patching, both development of improved patching techniques and of better overall management and decision criteria. Research indicates that better and more economical patching techniques are available than were being used prior to SHRP research. Overall recommendations on porthole patching are contained in the SHRP manual entitled *Materials and Procedures for the Repair of Potholes in Asphalt-Surfaced Pavements* [1]. This manual not only gives guidelines for selecting improved techniques but also gives detailed examples comparing the cost-effectiveness of different alternatives. More detailed discussions of SHRP research on pothole patching are given in other reports [2, 3]. John Hibbs and Shashikant Shah [4] have summarized some of this cost-effectiveness information as shown in Table 71. This table summarizes information on four techniques: local throw and roll (TAR); proprietary throw and roll (TAR); semi-permanent technique (SP); and spray injection (SI).

One of the difficulties with making an estimate of the SHRP research results is that there is no comprehensive information covering the specific techniques that states and local governments are currently using. In this research, it is assumed that the current practice is best represented by the two techniques specified as the local throw-and-roll technique and the local semi-permanent technique, or about $43 per cubic feet. It further is assumed that the implementation of SHRP results will result in costs similar to those specified as proprietary or spray injection, or about $10 per cubic foot. The cost saving therefore is represented as a reduction of about 77 percent. However, it is unlikely that all agencies would be able to realize such a large savings. Therefore, a more conservative 25 percent reduction in costs is used in this analysis. This saving is applied to the current annual cost for pothole patching for state governments which is estimated at about $350 million per year, and local governments of about $725 million per year. Using these values, the maximum annual savings is estimated at $268 million. In addition to the agency savings, there would be a significant reduction in user costs as well, which can not be estimated here.

Using the maximum annual amount of $268 million in agency costs, Tables 72, 73, and 74 summarize the overall cost savings for slow, moderate, and fast implementation rates of SHRP results over a 20-year period. Each of these implementation scenarios assumes that implementation is low in early years and gradually increases over time, reaching ultimate implementation percentages of 25 percent, 50 percent, and 100 percent for the slow, moderate, and fast implementation scenarios, respectively. The present value of benefits for the 20-year period is estimated by discounting future benefits to the present using a discount rate of five percent. Twenty-year benefits are estimated at about $295 million for slow implementation, $566 million for moderate implementation, and $1,107 for fast implementation.

Table 71. Cost-Effectiveness and Other Data on Pavement Patching

Material Type	Local	Proprietary	Local	Spray Injection
Procedure*	TAR	TAR	SP	SI
Material, $/ton	20	85	20	0
Crew, $/day	300	300	600	0
Traffic. $/day	250	250	250	250
Equipment, $/day	80	80	130	930
Productivity, tons/day	4.0	4.0	1.5	4.0
Tons Required	200	200	75	200
Patch Life, months	3	21	12	21
5-Year Cost, $	710,000	139,000	252,000	168,570
Cost Effectiveness, $/cf	44	9	42	11

* TAR=Throw-and-Roll, SP=Semi-Permanent, SI=Spray Injection

Table 72. Total Pothole Cost Savings with a Slow Implementation Scenario.

Year	Implementation Rate (Percent)	Discounted Agency Savings (Million $)
1	1.0	2.68
2	1.3	3.32
3	1.8	4.38
4	2.4	5.56
5	3.1	6.84
6	4.0	8.40
7	4.9	9.80
8	5.9	11.24
9	7.1	12.88
10	8.3	14.34
11	9.6	15.79
12	11.0	17.24
13	12.5	18.65
14	14.0	19.90
15	15.7	21.25
16	17.4	22.43
17	19.2	23.57
18	21.0	24.55
19	23.0	25.61
20	25.0	26.51
20-Year Total		294.94
Equiv. Ann. Tot.		23.67

Source: Calculated using $268 million in potential annual savings and a 5 percent discount rate. Equivalent annual totals are calculated using a factor of 12.4622, to convert the 20 year totals into annual values.

Table 73. Total Cost Savings with a Moderate Implementation Scenario.

Year	Implementation Rate (Percent)	Discounted Agency Savings (Million $)
1	1.0	2.68
2	1.7	4.34
3	2.7	6.56
4	3.9	9.03
5	5.4	11.91
6	7.1	14.91
7	9.0	18.00
8	11.1	21.14
9	13.4	24.31
10	15.9	27.47
11	18.5	30.44
12	21.4	33.53
13	24.4	36.41
14	27.6	39.23
15	30.9	41.83
16	34.4	44.35
17	38.1	46.78
18	41.9	48.99
19	45.9	51.11
20	50.0	53.03
20-Year Total		566.03
Equiv. Ann. Tot.		45.42

Source: Calculated using $268 million in potential annual savings and a 5 percent discount rate. Equivalent annual totals are calculated using a factor of 12.4622, to convert the 20 year totals into annual values.

Table 74. Total Pothole Cost Savings with a Fast Implementation Scenario.

Year	Implementation Rate (Percent)	Discounted Agency Savings (Million $)
1	1.0	2.68
2	2.4	6.13
3	4.3	10.45
4	6.8	15.74
5	9.8	21.61
6	13.3	27.93
7	17.1	34.20
8	21.4	40.76
9	26.0	47.16
10	31.0	53.55
11	36.4	59.89
12	42.2	66.12
13	48.3	72.08
14	54.7	77.74
15	61.5	83.25
16	68.6	88.43
17	76.0	93.31
18	83.7	97.87
19	91.7	102.12
20	100.0	106.06
20-Year Total		1,107.07
Equiv. Ann. Total		88.83

Source: Calculated using $268 million in potential annual savings and a 5 percent discount rate. Equivalent annual totals are calculated using a factor of 12.4622, to convert the 20 year totals into annual values.

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CHAPTER 6

LIFE-CYCLE EFFECTS OF SNOW AND ICE REMOVAL

OBJECTIVES

Snow and ice control costs local and state highway agencies in excess of $1.8 billion annually. While the elimination or reduction of snow and ice improves the safety of our highways and provides year-round mobility, the widespread use of salt (about 10 million tons annually) for this purpose accelerates the deterioration of highways, bridges and vehicles. In addition, snow and ice removal concentrates salts near the roadside which may cause damage to vegetation and water supplies (1).

The major objectives of the SHRP snow and ice control research were to: 1) develop more cost-effective ways to remove the build up of snow and ice on highways, 2) increase highway safety while reducing motorist accident costs, 3) reduce corrosive effects on pavements, structures and vehicles and 4) mitigate adverse environmental impact.

RESEARCH PROJECT

The proposed SHRP research on snow and ice control identified five projects:

1. prevention of ice-pavement bond;
2. destruction of ice-pavement bond;
3. development of improved displacement plows;
4. improved methods of controlling blowing snow; and
5. management of snow and ice control operations.

ACCOMPLISHMENTS

Snow and ice control research and development produced 13 products that can be grouped into five areas: anti-icing technology, ice disbonding, snow drift control, snow plow design and road weather information systems. A brief summary of the types of products available from each of these areas is presented below.

Anti-icing Technology

Anti-icing products included a manual that provides guidance on when and how to apply chloride and non-chloride agents for optimum performance with a minimum amount of chemicals. The manual also evaluates equipment application rates.

Ice Disbonding

Two products were developed related to ice disbonding: 1) Handbook on Deicer Test Methods and 2) salt spreader TAM. The handbook describes 12 tests that evaluate ice-control chemicals. These test assess performance qualities, operational parameters, environmental, health and safety aspects and compatibility with metals, concrete and asphalt.

The salt spreader consists of an impact atenuator with a spreader attachment mounted on the rear of the truck. The device distributes salt and provides a “crash cushion” which makes salt spreading safer.

Snow Plow Design

Research-based improvements in snow fence design and placement optimize drift control on highways. The fences also reduce snow and ice removal costs and provide a safe pavement surface. Snow drift control products are included the *Snow Fence Guide and Snow Fence Engineering Design Manual.*

Road Weather Information Systems

Road weather information systems (RWIS) enable better scheduling of crews based on more precise knowledge of actual storm conditions and allow improved development of chemical anti-icing or deicing strategies. The systems incorporate pavement temperature sensors and ice detectors, meteorological sensors that measure the atmosphere and weather forecasts from various sources. *Guide for Road Weather Information Systems* and the customized weather prediction system were products of this research.

POST-SHRP ACTIVITIES

Additional research, development and implementation activities resulted from the SHRP research on snow and ice. The centerpiece of the snow and ice implementation effort is the FHWA technology transfer “Showcase.” The Showcase is one of the primary technology transfer activities. Examples of these activities include the “Blizzard of 96" conference held in Washington, D.C. and the Western and Eastern States Snow and Ice conference.

RWIS’ approach to snow and ice control grew at a rapid rate during SHRP. By 1994, more than 750 RWIS sites were established throughout the country.

In 1993, 15 states participated in a FHWA two-year study titled Test and Evaluation Project No.28 that evaluated the use of anti-icing technology.

Nine states have experimented with the timing of the application of various anti-icing chemicals under different climate conditions. Results indicate that anti-icing operations are effective in a large number of storm conditions.

Twelve new test procedures have been developed to evaluate the effectiveness and environmental impact of deicers. AASHTO has included one of the procedures in its provisional standards.

Snow scoop design improvements have been pursued by industry and several states.

Calculation of Agency and Motorist Savings of Anti-Icing Operations

There are several SHRP products in the area of snow and ice removal that potentially could result in significant cost savings as the products are implemented over time. These products include anti-icing chemicals, de-icing chemicals, snow plow cutting edge, weather forecasting systems and snow fences. However, the combination of an anti-icing strategy and a weather forecasting system has received the most attention for potential implementation in the states, and is used in this section to make estimates of the potential cost savings to both the transportation agencies and the motorists using the highways. The implementation involves using a road weather information system to more accurately predict potential snow and ice conditions on bridges and highways, and the use of anti-icing chemicals to pretreat the affected facilities and reduce or eliminate the need for multiple treatments of traditional de-icing methods involving sand and salt.

A SHRP study was completed by Midwest Research Institute to investigate and recommend improved anti-icing operations. Their research is contained in a report titled *Development of Anti-Icing Technology* (1). A section of the report is devoted to making a preliminary estimate of the benefits and costs of improved anti-icing operations on U.S. bridges and highways. Transportation agency cost savings were developed for reductions in labor, vehicle operations and materials, due to the reduced number of passes required during a storm period. These savings are partially offset by the increased equipment cost to implement the anti-icing treatments. The agency cost savings estimated by Midwest Research for five levels of winter storm severity are presented in Table 75. These costs were based principally on cost information provided by Minnesota DOT. The agency savings vary from $1,266 to $30,152 per typical maintenance truck route per year. The size of the savings depends on the storm hours per winter the agency has to have winter maintenance operations underway.

Impacts on user costs were estimated using accident rate information supplied by New York DOT. The reduction in exposure to ice and snow conditions was used to estimate the reductions in accidents due to a fully implemented anti-icing operation. The estimated savings in reduced accidents are presented in Table 75. The savings vary from $11,924 for the 100 storm hours category to $107,312 for the 900 storm hour category. The total annual cost savings per truck route ranges from $13,900 to $137,464.

Table 75. Annual Cost Savings for a Typical Truck Route.

	Categories of Winter Storm Severity				
Storm Hours per Winter	100	300	500	700	900
Storms per Winter	5	12	18	25	30
Annual Agency Cost Savings ($)					
Labor	43	332	689	978	1,403
Vehicle Operations	40	312	648	920	1,320
Materials	3,160	9,673	16,251	22,764	29,406
Equipment	-1,977	-1,977	-1,977	-1,977	-1,977
Total	1,266	8,340	15,611	22,685	30,152
Annual Motorist Accident Cost Savings ($)	11,924	35,771	59,618	83,465	107,312
Total Annual Cost Savings per Truck Route ($)	13,190	44,111	75,229	106,150	137,464

In order to make national estimates of anti-icing implementation the estimates in Table 76 were first converted into cost savings per highway mile. This was done using the average truck route length of 40 lane-miles presented in the Midwest Research report (1), and converting the 40 lane-miles into 20 miles coverage per truck route. This conversion of the cost savings are presented in Table 76. The total cost savings vary from about $660 per mile up to $6,870 per mile.

The cost savings estimates in Table 76 compare favorably with the case study information collected in this study. For example in Washington, Location "A", two 20-mile highway sections were compared during a 10-day period of ice and freezing conditions. The total cost for traditional methods was $4,400, compared to the anti-icing treatment using liquid magnesium chloride of $383. The savings were $4,017, which would translate to about $200 per mile. This would put the savings between the estimate for 100 storm hours and 300 storm hours in Table 75, certainly a reasonable place in the range shown in the table. The case study for Boulder, Colorado, showed similar large savings using anti-icing techniques. The estimate for using a magnesium chloride anti-icing strategy cost about $2,500 per lane mile as compared to $5,200 per lane mile for sanding operations. That translates to a savings of $5,400 per mile. That number is much higher than any estimate in Table 76, including the $1,506 for the most severe category of 900 storm hours per winter. It should be noted that one case study found an increase in cost using anti-icing chemicals. New Hampshire found, using potassium acetate, that the anti-icing operation cost over $9,600 per mile versus $350 per mile for salt and sand. No details are given for the cost estimates, but the case studies may indicate that magnesium chloride is more cost-effective than potassium acetate as an anti-icing chemical. Overall it is concluded that an anti-icing operation can result in significant cost savings, and the numbers in Table 76 are reasonable, given the limited implementation experience currently available.

In order to aggregate the cost-savings estimates in Table 76, it is necessary to determine the highway mileage applicable to each winter storm severity category. Historical average annual snowfall amounts from the "Statistical Abstract of the United States" (3, p. 245) were used for this purpose. Each severity category was associated with a range of snowfall for the cities listed in each state. The breakdown of mileage by state is shown in Table 77. In those states where the snowfall is given for only one city, all the state's mileage is assigned to the corresponding category. For those states with multiple snowfalls listed, the mileage is apportioned between the appropriate categories. While the amount of snowfall is not the only factor affecting total storm hours, all factors are highly correlated and the table gives a rough approximation to categorize each state's highway network. The last row in Table 77 gives the results of that breakdown as a percentage of the entire highway network. It shows 24 percent of the highway network in the lowest severity category of 100 storm hours per year, with lower percentages going up the severity scale. The highest severity category of 900 storm hours per year has only 3 percent of the highway network. A total of 56 percent of the U.S. highway network is estimated to fall into one of these winter storm severity categories.

Table 78 gives the cost savings aggregated over the U.S. highway network. The results in Table 78 show that if anti-icing operations were fully implemented, the potential savings would be about $366 million in reduced agency costs and $1.35 billion savings to motorists, for a total of $1.67 billion annually. The estimates are made using the total highway mileage in the U.S., excluding the local functional class. The local functional class was excluded because these roads tend to be low volume roads that do not provide connections to the overall highway network, and would be less likely to benefit significantly from the improved ice and snow technology evaluated here.

To put the estimated cost savings from Table 78 in perspective, Appendix C gives the total 1994 expenditure by state and local agencies for snow and ice removal at $2.094 billion. Therefore if the anti-icing technology were fully implemented by every state agency, the potential savings would be about 17.7 percent (366/2094) of the total expenditures on snow and ice removal. Of course, the anti-icing technology will not be immediately implemented by all agencies and may never be used in all situations. There will be an implementation process that will take place as agencies further test the cost-saving potential and gradually implement successful materials and procedures throughout their highway networks. Table 79 gives the discounted total cost savings for a slow implementation scenario over a 20 year period. The implementation rate starts out at a very slow level and gradually accelerates to reach 50 percent implementation after 20 years. Even with this very conservative implementation pattern, the total discounted cost savings amount to a very impressive $3.5 billion dollars. Table 80 gives similar estimates using a moderate implementation scenario which reaches 75 percent implementation after 20 years. The total estimated cost savings are estimated to be $5.2 billion. Table 80 gives savings estimates for a fast implementation scenario which reaches 100 percent implementation after 20 years. The total estimated savings are about $6.9 billion.

It is apparent that the SHRP products developed for implementing anti-icing operations in the United States have very large potential benefits. Using very conservative assumptions and cost-saving estimates, the total benefits over a 20 year implementation process would be at least between 3.5 and 6.9 billion dollars.

Table 76. Annual Cost Savings per Mile.

	Categories of Winter Storm Severity				
Storm Hours per Winter	100	300	500	700	900
Storms per Winter	5	12	18	25	30
Annual Agency Cost Savings ($)					
Labor	2.15	16.60	34.45	48.90	70.15
Vehicle Operations	2.00	15.60	32.40	46.00	66.00
Materials	158.00	483.65	812.55	1,138.20	1,470.30
Equipment	-98.85	-98.85	-98.85	-98.85	-98.85
Total	63.30	417.00	780.55	1,134.25	1,507.60
Annual Motorist Accident Cost Savings ($)	596.20	1,788.55	2,980.90	4,173.25	5,365.60
Total Annual Cost Savings per Mile ($)	659.50	2,205.55	3,761.45	5,307.50	6,873.20

Source: Calculated from Table 75, assuming an average 20 mile truck route.

Table 77. Distribution of U.S. Highway Mileage by Storm Severity Category (cont'd).

State	Category of Snowfall in Inches and Storm Hours per Winter						
	0-15 in.	15-30 in.	30-45 in.	45-60 in.	50-75 in.	75+ in.	Total
	. 0 hrs.	100 hrs.	300 hrs.	500 hrs.	700 hrs.	900 hrs.	
AL	29,896						29,896
AK						5,083	5,083
AZ	14,660						14,660
AR	27,242						27,242
CA	62,764						62,764
CO					25,856		25,856
CT				6,453			6,453
DE		1,599					1,599
DC		448					448
FL	29,257						29,257
GA	37,483						37,483
HI	1,615						1,615
ID		13,842					13,842
IL		18,715	18,714				37,429
IN		31,807					31,807
IA			41,717				41,717
KS		43,193					43,193
KY		23,920					23,920
LA	18,764						18,764
ME					8,621		8,621
MD		9,244					9,244
MA			11,829				11,829
MI			9,873	9,873	9,873	9,873	39,491
MN				14,513	14,086	14,086	42,685
MS	23,254						23,254
MO		35,816					35,816
MT				23,640			23,640
NE		29,115					29,115
NV		8,219					8,219
NH					4,525		4,525
NJ		10,472					10,472
NM	12,330						12,330
NY	18,246				9,122	9,122	36,490

Table 77. Distribution of U.S. Highway Mileage by Storm Severity Category (cont'd).

NC		27,854					27,854
ND	25,234						25,234
OH		17,321	8,661	8,661			34,642
OK	34,281						34,281
OR	26,102						26,102
PA		17,535	17,534				35,069
RI			1,764				1,764
SC	21,075						21,075
SD			26,239				26,239
TN	27,802						27,802
TX	94,085						94,085
UT				11,994			11,994
VT						4,750	4,750
VA	23,631						23,631
WA	12,566			12,565			25,131
WV			12,337				12,337
WI				34,001			34,001
WY				15,170			15,170
Total	540,287	289,100	148,668	136,869	77,083	42,914	1,229,920
% Total Mileage	44	24	12	11	6	3	100

Source: Total highway miles, excluding local functional class, taken from (2), Table HM-20, p. V-14. Snowfall by state taken from (3), p. 245.

Table 78. Total Annual Cost Savings with Full Implementation in State Agencies.

	Categories of Winter Storm Severity					
Storm Hours per Winter	100	300	500	700	900	Total
Storms per Winter	5	12	18	25	30	
U.S. Mileage in Each Category (Percent)	24	12	11	6	3	56
Annual Agency Cost Savings (Million $)						
Labor	0.63	2.45	4.66	3.61	2.59	13.94
Vehicle Operations	0.59	2.30	4.38	3.39	2.44	13.11
Materials	46.64	71.38	109.93	83.99	54.25	366.20
Equipment	-29.18	-14.59	-13.37	-7.29	-3.65	-68.08
Total	18.68	61.55	105.60	83.70	55.63	325.16
Annual Motorist Accident Cost Savings (Million $)	175.99	263.97	403.29	307.97	197.98	1,349.19
Total Annual Cost Savings with Full Implementation (Million $)	194.67	325.52	508.89	391.67	253.60	1,674.35

Source: Calculated from Table 76 using percent highway miles and total highway miles in Table 77.

Table 79. Total Cost Savings with a Slow Implementation Scenario.

Year	Implementation Rate (Percent)	Discounted Agency Savings (Million $)	Discounted Motorist Savings (Million $)	Total Discounted Savings (Million $)
1	1.0	3.25	13.49	16.74
2	1.7	5.26	21.84	27.11
3	2.7	7.96	33.04	41.00
4	3.9	10.95	45.45	56.41
5	5.4	14.45	59.94	74.38
6	7.1	18.09	75.06	93.14
7	9.0	21.84	90.61	112.45
8	11.1	25.65	106.43	132.08
9	13.4	29.49	122.37	151.86
10	15.9	33.33	138.28	171.61
11	18.5	36.93	153.23	190.16
12	21.4	40.68	168.81	209.50
13	24.4	44.18	183.31	227.49
14	27.6	47.59	197.48	245.07
15	30.9	50.75	210.56	261.31
16	34.4	53.80	223.25	277.06
17	38.1	56.75	235.49	292.24
18	41.9	59.44	246.64	306.09
19	45.9	62.02	257.32	319.34
20	50.0	64.34	266.96	331.30
20-Year Total		686.76	2,849.59	3,536.35
Equiv. Ann. Tot.		55.11	228.66	283.77

Source: Calculated from Table 78, using a 5 percent discount rate. Equivalent annual totals are calculated using a factor of 12.4622, to convert the 20 year totals into annual values.

Table 80. Total Cost Savings with a Moderate Implementation Scenario.

Year	Implementation Rate (Percent)	Discounted Agency Savings (Million $)	Discounted Motorist Savings (Million $)	Total Discounted Savings (Million $)
1	1.0	3.25	13.49	16.74
2	2.0	6.19	25.70	31.89
3	3.5	10.32	42.83	53.15
4	5.4	15.17	62.94	78.10
5	7.6	20.33	84.36	104.69
6	10.2	25.99	107.83	133.81
7	13.0	31.54	130.88	162.43
8	16.2	37.44	155.33	192.77
9	19.7	43.36	179.90	223.25
10	23.5	49.26	204.38	253.64
11	27.5	54.90	227.78	282.67
12	31.8	60.46	250.85	311.31
13	36.3	65.73	272.72	338.44
14	41.1	70.87	294.07	364.95
15	46.2	75.87	314.82	390.70
16	51.5	80.55	334.23	414.78
17	57.0	84.91	352.31	437.21
18	62.8	89.09	369.67	458.76
19	68.8	92.96	385.70	478.66
20	75.0	96.51	400.44	496.95
20-Year Total		1,014.68	4,210.23	5,224.91
Equiv. Ann. Tot.		81.42	337.84	419.26

Source: Calculated from Table 78, using a 5 percent discount rate. Equivalent annual totals are calculated using a factor of 12.4622, to convert the 20 year totals into annual values.

Table 81. Total Cost Savings with a Fast Implementation Scenario.

Year	Implementation Rate (Percent)	Discounted Agency Savings (Million $)	Discounted Motorist Savings (Million $)	Total Discounted Savings (Million $)
1	1.0	3.25	13.49	16.74
2	2.4	7.43	30.84	38.27
3	4.3	12.68	52.62	65.30
4	6.8	19.10	79.25	98.35
5	9.8	26.22	108.78	134.99
6	13.3	33.88	140.60	174.48
7	17.1	41.49	172.16	213.65
8	21.4	49.45	205.19	254.65
9	26.0	57.22	237.43	294.65
10	31.0	64.98	269.61	334.58
11	36.4	72.66	301.50	374.16
12	42.2	80.23	332.89	413.12
13	48.3	87.45	362.87	450.32
14	54.7	94.32	391.38	485.71
15	61.5	101.00	419.08	520.08
16	68.6	107.30	445.20	552.50
17	76.0	113.21	469.74	582.95
18	83.7	118.74	492.70	611.44
19	91.7	123.90	514.09	637.98
20	100.0	128.68	533.92	662.60
20-Year Total		1,343.20	5,573.34	6,916.54
Equiv. Ann. Tot.		107.78	447.22	555.00

Source: Calculated from Table 78, using a 5 percent discount rate. Equivalent annual totals are calculated using a factor of 12.4622, to convert the 20 year totals into annual values.

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CHAPTER 7

LIFE-CYCLE EFFECT ON WORK ZONES

OBJECTIVES

The major objectives of the SHRP work zone safety research program were to reduce work zone-related accidents and to increase worker productivity through improved materials, equipment and procedures.

RESEARCH PROJECTS

The proposed SHRP research on work zone safety identified four projects:

1. Evaluation of existing devices and procedures;
2. Development of guides for new traffic controls;
3. Development and testing of new traffic controls; and
4. Documentation for implementation.

WORK ZONE SAFETY RESEARCH

In 1994, 706 people were killed in highway work zones — an increase of 185 deaths from the previous year. This dramatic rise is a graphic reminder of how dangerous work zones are for both crews and motorists.

The concrete barriers used to protect highway construction workers are too heavy to be used on temporary rehabilitation and maintenance projects. This inspired SHRP research on the development of lightweight and conspicuous safety devices that effectively control traffic and protect workers. The devices also were designed for quick installation and removal to give crews more time to do their work.

SHRP Work Zone Safety Products

SHRP has developed nine products that are intended to improve the safety of work zone workers and/or auto passengers moving through work zones. Seven of these products have been implemented on a trial basis by at least one state. Two products, the portable Crash Cushion and the Queve-Length Detector have not yet had a reported trial use in the field.

None of the nine products have been in use for a long enough period to permit a valid evaluation of the potential accident reductions that could be attributed to each. However, a panel of roadside safety experts convened to review the state reports and provide a consensus estimate of the accident reductions that could reasonably be expected from additional implementation. In the process of developing an estimate the nine products were divided into two groups. The first group contained the five products that either had not had implementation reported or had experiences that raised questions about their design or functionality in the minds of the implementing state. They were:

1. Portable Rumble Strip;
2. Portable Crash Cushion;
3. Intrusion Alarm;
4. Robot Shadow Vehicle; and
5. Queue-Length Detector.

These five products have not demonstrated significant potential improvements in use at this time. Further development and additional field demonstrations may reveal future safety benefits from one or more of these products. However, they were assumed to provide no measurable safety benefit this time.

The second group included those four products that had a more extensive utilization and a more positive evaluation from the using states. These products were:

1. Flashing Stop/Slow Paddle;
2. All-Terrain Sign Stand;
3. Opposing Traffic Lane Dividers; and
4. Multi-Directional Barricade-Sign.

The effect of these devices is likely to be an increase in mobility through the work zone and more effective traffic control. Experience has shown, however, that increasing these factors does not always translate into increased safety. Their usability in the full range of work zones is also quiet varied. The Flashing Stop/Slow Paddle may be useful in practically all work zones while the All-Terrain Sign Stand would be used in broken or rolling terrain, and the opposing Traffic Lane Dividers are useful only in work zones on two land roadways.

The expert panel did not feel that any of these devices had been in use long enough or used widely enough to permit developing a safety improvement estimate on each one individually. Taken as a group, however, the panel felt that they should, when implemented over the next 20 years, contribute up to a five percent savings in the number of work zone accidents each year. For benefit/cost estimating purposes, it is further recommended that because of the non-uniform usage and uncertainty in rate of implementation, an average of two percent accident reduction per year be used.

Calculation of Agency and Motorist Savings of Work Zone SHRP Products

There are four SHRP products in the work zone safety area that have the greatest potential for implementation. These are:

1. Flashing Stop/Slow Paddle;
2. All-Terrain Sign Stand;
3. Opposing Traffic Lane Dividers; and
4. Multi-Directional Barricade-Sign.

In order to make estimates of potential cost savings, two work zone lengths are assumed, a 3 mile work zone and a 0.5 mile work zone. The estimates of costs of implementation assume that 2 flashing stop/slow paddles would be used and opposing lane dividers placed every 500 feet. It is further assumed that the products would last an average of 4 years and would represent an incremental cost 50 percent higher than current techniques. This gives an annual cost of $429 for the 3 mile work zone and $222 for the 0.5 mile work zone.

The cost per work zone is then applied to the total estimated work zones in the United States. According to the *Highway Statistics 1994*, a 5-year average of 14,790 miles of projects are underway each year in the federal-aid system of highways in the U.S. (excluding new location and relocation). If 50 percent have work zones set up any given time, then that would give a total of 2,465 work zones 3 miles long or 14,790 0.5 miles long. This gives an annual implementation cost of $1.06 million if all work zones are 3 miles long and $3.28 million if all work zones are 0.5 miles long. There is no available information on the length or distribution of lengths of work zones, so the average of these two work zone lengths is used to estimate the overall implementation costs. Taking an average of the two gives a cost of $2.17 million per year. This is the amount shown in Table 82.

The potential accident cost savings of SHRP products are calculated based on the reduction in workzone related accidents. The total number of work zone accidents in 1994 (not related to alcohol influence) is estimated to be 706 fatal accidents, 4,942 injury accidents and 20,885 property damage only (PDO) accidents. The number of fatal and injury accidents are from FHWA, adjusted for 20 percent alcohol related accidents. The PDO accidents are calculated from average accident rates in the MicroBENCOST default data set. The values for each accident category are taken from the FHWA recommended values to be used in evaluating highway projects. The total potential savings of SHRP product implementation was estimated by a panel of experts to be about 5 percent, with approximately 2 percent if implementation over time is taken into account. Since the implementation rates are built into each implementation scenario, the 5 percent number is used as the potential savings for full implementation. The total potential accident savings are divided between agency and user savings using numbers provided by the National Highway Traffic Safety Administration, which estimates that about 14 percent of total workzone fatalities were construction workers/pedestrians.

The total potential cost savings, given in Table 82, is estimated to be $101.78 million. These savings can only be realized through implementation of the SHRP products by state and local agencies. This implementation process will not occur immediately, but will gradually increase over time. For that reason, three implementation scenarios are used to estimate the benefits, a slow implementation scenario reaching 50 percent implementation in 20 years, a moderate implementation scenario reaching 75 percent in 20 years, and a fast implementation scenario reaching 100 percent in 20 years. Even with these very conservative implementation scenarios, substantial cost savings can be expected, ranging from $215 million to $420 million over twenty years. See Tables 83, 84 and 85 for the three scenarios.

Table 82. Estimated Savings of SHRP Work Zone Safety Products

	Accident Category			
	Fatal	Injury	PDO	Total
No. Work Zone Related Accidents	706	4,942	20,885	
Accident Value (Mill. $)	2.709	0.0248	0.0021	
Total Work Zone Accident Cost (Mill. $)	1,912.55	1,225.62	43.86	3,182.03
SHRP Accident Savings (Mill. $) (5% of Total Work Zone Cost)	95.63	6.13	2.19	103.95
Annual Agency Savings with Full Implementation (Mill. $)				
Accident Savings (14%)	13.39	0.86	0.31	14.55
Implementation Cost				-2.17
Net Savings				12.38
Annual Motorist Savings with Full Implementation (86%) (Mill. $)	82.24	5.27	1.88	89.40
Total Annual Savings with Full Implementation (Mill. $)				101.78

Table 83. Total Cost Savings with a Slow Implementation Scenario.

Year	Implementation Rate (Percent)	Discounted Agency Savings (Million $)	Discounted Motorist Savings (Million $)	Total Discounted Savings (Million $)
1	1.0	0.12	0.89	1.02
2	1.7	0.20	1.45	1.65
3	2.7	0.30	2.19	2.49
4	3.9	0.42	3.01	3.43
5	5.4	0.55	3.97	4.52
6	7.1	0.69	4.97	5.66
7	9.0	0.83	6.00	6.84
8	11.1	0.98	7.05	8.03
9	13.4	1.12	8.11	9.23
10	15.9	1.27	9.16	10.43
11	18.5	1.41	10.15	11.56
12	21.4	1.55	11.19	12.73
13	24.4	1.68	12.15	13.83
14	27.6	1.81	13.08	14.90
15	30.9	1.93	13.95	15.98
16	34.4	2.05	14.79	16.84
17	38.1	2.16	15.60	17.76
18	41.9	2.26	16.34	18.61
19	45.9	2.36	17.05	19.41
20	50.0	2.45	17.69	20.14
20-Year Total		26.15	188.81	214.96
Equiv. Ann. Tot.		2.10	15.15	17.25

Table 84. Total Cost Savings with a Moderate Implementation Scenario.

Year	Implementation Rate (Percent)	Discounted Agency Savings (Million $)	Discounted Motorist Savings (Million $)	Total Discounted Savings (Million $)
1	1.0	0.12	0.89	1.02
2	2.0	0.24	1.70	1.94
3	3.5	0.39	2.84	3.23
4	5.4	0.58	4.17	4.75
5	7.6	0.77	5.59	6.36
6	10.2	0.99	7.14	8.13
7	13.0	1.20	8.67	9.87
8	16.2	1.43	10.29	11.72
9	19.7	1.65	11.92	13.57
10	23.5	1.88	13.54	15.42
11	27.5	2.09	15.09	17.18
12	31.8	2.30	16.62	18.92
13	36.3	2.50	18.07	20.57
14	41.1	2.70	19.48	22.18
15	46.2	2.89	20.86	23.75
16	51.5	3.07	22.15	25.21
17	57.0	3.23	23.34	26.58
18	62.8	3.39	24.49	27.89
19	68.8	3.54	25.56	29.10
20	75.0	3.68	26.53	30.21
20-Year Total		38.64	228.96	317.60
Equiv. Ann. Tot.		3.10	22.38	25.49

Table 85. Total Cost Savings with a Fast Implementation Scenario.

Year	Implementation Rate (Percent)	Discounted Agency Savings (Million $)	Discounted Motorist Savings (Million $)	Total Discounted Savings (Million $)
1	1.0	0.12	0.89	1.02
2	2.4	0.28	2.04	2.33
3	4.3	0.48	3.49	3.97
4	6.8	0.73	5.25	5.98
5	9.8	1.00	7.21	8.21
6	13.3	1.29	9.32	10.61
7	17.1	1.58	11.41	12.97
8	21.4	1.88	13.60	15.48
9	26.0	2.18	15.73	17.91
10	31.0	2.47	17.86	20.34
11	36.4	2.77	19.98	22.74
12	42.2	3.06	22.06	25.11
13	48.3	3.33	24.04	27.37
14	54.7	3.59	25.93	29.52
15	61.5	3.85	27.77	31.61
16	68.6	4.09	29.50	33.58
17	76.0	4.31	31.12	35.44
18	83.7	4.52	32.65	37.17
19	91.7	4.72	34.06	38.78
20	100.0	4.90	35.38	40.28
20-Year Total		51.15	369.28	420.43
Equiv. Ann. Tot.		4.10	29.63	33.74

CHAPTER 8

AGENCY AND MOTORIST COST SAVINGS OF THE SHRP LTTP PROGRAM

The long-term pavement performance (LTPP) portion of the SHRP program has not been completed yet, so it is difficult to make an estimate of the potential benefits of the research. However, preliminary results indicate that the improved pavement design equations resulting from the research will have a significant and positive impact on certain pavements that have not been designed correctly. For purposes of this analysis, pavements that are not designed correctly require rehabilitation after 5 years, which will last an additional 7 years. A second rehabilitation will last an additional 8 years. With improved design equations, the pavements will require a single rehabilitation after 10 years, and will last an additional 10 years. It is estimated that about 25 percent of the higher volume highways are affected by inadequate designs and lower pavement life. Therefore in this analysis, 25 percent of the highways 4 lanes and greater are used to estimate the potential benefits of the LTPP program. These mileage totals are shown in Table 86.

Table 87 gives the calculated PSI values for each highway type over a 40 year analysis period. A 40 year analysis period was chosen because it is consistent with the other computer calculations of SHRP products and allows enough time to pass that each scenario goes through at least two life cycles.

The highway type categories from Table 86 and the MicroBENCOST PC computer program were used to make cost savings estimates of the LTPP scenarios. In addition an annual traffic growth rate of 2.1 percent was assumed, consistent with the other SHRP product computer runs.

The results of the analysis for each highway type is given in Table 88. Detailed MicroBENCOST output are given in Appendix 2. The agency cost savings consist of fewer required rehabilitations for over the 40 life cycle in the analysis. The motorist cost savings are broken down into two categories, delay savings and reduction in vehicle operating costs (VOC). As expected, the greatest savings are for the higher volume facilities and much lower savings for the low-volume highways. The urban freeway, for example, would generate more than $1.59 million dollars per mile in motorist savings and $552,000 per mile in agency savings. In contrast the rural other 4-lane highway would be about $169,000 in motorist savings and $238,000 in agency savings.

In order to compare the cost savings, it is necessary to convert the total savings per mile in Table 88 to an annual cost savings. This can be done using equivalent uniform annual cost factors. The factor for a uniform series over 40 years using a 5 percent discount rate is 17.16. By dividing each number in Table 88 by 17.16, they can be converted into annual savings. These annual numbers are given in Table 89. The numbers range from $124,926 for an urban freeway to $23,747 for a rural other 4-lane highway.

These annual cost savings per mile can then be aggregated using the total asphalt mileage that could potentially benefit from the improved design equations. As mentioned above, 25 percent of the total 4 lane or more mileage in the U.S. is used to calculate the total savings. The total annual cost savings are given in Table 90. This table shows that a total of about $2.2 billion could be saved annually in the U.S. using the improved maintenance strategies and timing of those strategies. Of this total, about $800 million would represent annual agency savings, and $1.4 billion represents annual motorist savings.

The numbers in Table 90 represent the total potential annual savings if all agencies immediately implemented the improved maintenance strategies. These savings can only be realized with full implementation through all state and local transportation agencies in the U.S. That implementation process is expected to be a slow, gradual process as case studies are tried and improvements made to the existing recommendations. Tables 91, 92, and 93 give estimates of the total estimated benefits over 20 years assuming a slow implementation scenario, a moderate implementation scenario, and a fast implementation scenario. The slow implementation scenario assumes a 50 percent implementation after 20 years, the moderate implementation scenario assumes a 75 percent implementation after 20 years, and the fast implementation scenario assumes a 100 percent implementation occurring after 20 years. These scenarios give a reasonable range for the expected benefits to the improved maintenance strategies as developed in SHRP. The potential cost savings are substantial, even with these very modest implementation scenarios, ranging from $4.66 billion to $9.12 billion over the next twenty years. The savings to agencies alone would range from $1.7 to $3.3 billion in present value dollars.

Table 86. U.S. Highway Mileage of 4 Lanes or Greater

	Total Mileage	25% Affected Mileage
Urban		
Freeways	25,214	6,304
Other 4-Ln. Highways	59,452	14,863
Total	84,666	21,167
Rural		
Freeways	43,763	10,941
Other 4-Ln. Highways	24,693	6,173
Total	68,456	17,114
Overall Total	153,122	38,281

Source: *Highway Statistics*, 1994 (1), Table HM-57, pp. V46-V47.

Table 87. Yearly PSI Values Used for LTPP Strategies.

Year	Freeway		4-Lane Divided	
	Current Condition	Improved Condition	Current Condition	Improved Condition
1	4.27	4.30	4.17	4.20
2	4.16	4.29	4.05	4.19
3	3.92	4.27	3.79	4.17
4	3.54	4.22	3.38	4.12
5	3.00	4.15	2.80	4.04
6	4.29	4.03	4.19	3.91
7	4.24	3.87	4.13	3.74
8	4.13	3.65	4.02	3.50
9	3.96	3.36	3.84	3.19
10	3.72	3.00	3.58	2.80
11	3.40	4.30	3.23	4.20
12	3.00	4.29	2.80	4.19
13	4.29	4.27	4.19	4.17
14	4.25	4.22	4.15	4.12
15	4.18	4.15	4.07	4.04
16	4.06	4.03	3.94	3.91
17	3.88	3.87	3.75	3.74
18	3.65	3.65	3.50	3.50
19	3.36	3.36	3.19	3.19
20	3.00	3.00	2.80	2.80
21	4.27	4.30	4.17	4.20
22	4.16	4.29	4.05	4.19
23	3.92	4.27	3.79	4.17
24	3.54	4.22	3.38	4.12
25	3.00	4.15	2.80	4.04
26	4.29	4.03	4.19	3.91
27	4.24	3.87	4.13	3.74
28	4.13	3.65	4.02	3.50
29	3.96	3.36	3.84	3.19
30	3.72	3.00	3.58	2.80
31	3.40	4.30	3.23	4.20
32	3.00	4.29	2.80	4.19
33	4.29	4.27	4.19	4.17
34	4.25	4.22	4.15	4.12
35	4.18	4.15	4.07	4.04
36	4.06	4.03	3.94	3.91
37	3.88	3.87	3.75	3.74
38	3.65	3.65	3.50	3.50
39	3.36	3.36	3.19	3.19
40	3.00	3.00	2.80	2.80

Table 88. Discounted Cost Savings per Mile over a 40 Year Analysis Period (Thous. $)

	Urban		Rural	
	Freeway	Other 4-Lane	Freeway	Other 4-Lane
Agency Cost Savings Total	552.00	378.00	295.00	238.00
Motorist Cost Savings Delay VOC Total	 319.94 1,271.68 1,591.62	 133.35 357.49 490.84	 85.73 437.00 522.73	 43.68 125.79 169.47
Total Cost Savings	2143.62	868.84	817.73	407.47

Table 89. Equivalent Uniform Annual Cost Savings per Mile ($).

	Urban		Rural	
	Freeway	Other 4-Lane	Freeway	Other 4-Lane
Agency Cost Savings Total	32,170	22,029	17,192	13,870
Motorist Cost Savings Delay VOC Total	 18,646 74,111 92,757	 7,771 20,834 28,605	 4,996 25,458 30,464	 2,546 7,331 9,876
Total Cost Savings	124,926	50,634	47,656	23,747

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Table 90. Total Annual Cost Savings (Million $)

	Urban		Rural		Total
	Freeway	Other 4-Lane	Freeway	Other 4-Lane	
Agency Cost Savings Total	202.78	327.42	188.09	85.62	803.92
Motorist Cost Savings					
Delay	117.53	115.51	54.66	15.71	303.41
VOC	467.16	309.65	278.63	45.25	1,100.70
Total	584.69	425.16	333.30	60.97	1,404.12
Total Cost Savings	787.47	752.58	521.39	146.59	2,208.04

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Table 91. Total Cost Savings with a Slow Implementation Scenario.

Year	Implementation Rate (Percent)	Discounted Agency Savings (Million $)	Discounted Motorist Savings (Million $)	Total Discounted Savings (Million $)
1	1.0	8.04	14.04	22.08
2	1.7	13.02	22.73	35.75
3	2.7	19.69	34.39	54.07
4	3.9	27.08	47.30	74.39
5	5.4	35.71	62.38	98.09
6	7.1	44.72	78.11	122.83
7	9.0	53.99	94.30	148.29
8	11.1	63.42	110.76	174.18
9	13.4	72.91	127.35	200.26
10	15.9	82.40	143.91	226.31
11	18.5	91.30	159.47	250.78
12	21.4	100.59	175.69	276.27
13	24.4	109.23	190.78	300.00
14	27.6	117.67	205.52	232.19
15	30.9	125.46	219.13	344.60
16	34.4	133.02	232.34	365.36
17	38.1	140.32	245.08	385.39
18	41.9	146.96	256.68	403.65
19	45.9	153.33	267.80	421.13
20	50.0	159.07	277.83	436.90
20-Year Total		1,697.93	2,965.59	4,663.52
Equiv. Ann. Tot.		136.25	237.97	374.21

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Table 92. Total Cost Savings with a Moderate Implementation Scenario.

Year	Implementation Rate (Percent)	Discounted Agency Savings (Million $)	Discounted Motorist Savings (Million $)	Total Discounted Savings (Million $)
1	1.0	8.04	14.04	22.08
2	2.0	15.31	26.75	42.06
3	3.5	25.52	44.58	70.10
4	5.4	37.50	65.50	103.00
5	7.6	50.27	87.79	138.06
6	10.2	64.25	112.22	176.47
7	13.0	77.99	136.21	214.20
8	16.2	92.56	161.66	254.21
9	19.7	107.19	187.22	294.41
10	23.5	121.78	212.70	334.48
11	27.5	135.72	237.05	372.77
12	31.8	149.47	261.06	410.54
13	36.3	162.50	283.82	446.31
14	41.1	175.22	306.04	481.27
15	46.2	187.59	327.64	515.23
16	51.5	199.15	347.83	546.98
17	57.0	209.92	366.65	576.57
18	62.8	220.27	384.72	604.99
19	68.8	229.82	401.41	631.23
20	75.0	238.60	416.74	655.35
20-Year Total		2,508.67	4,381.62	6,890.30
Equiv. Ann. Tot.		201.30	351.59	552.90

Table 93. Total Cost Savings with a Fast Implementation Scenario.

Year	Implementation Rate (Percent)	Discounted Agency Savings (Million $)	Discounted Motorist Savings (Million $)	Total Discounted Savings (Million $)
1	1.0	8.04	14.04	22.08
2	2.4	18.38	32.09	50.47
3	4.3	31.35	54.76	86.12
4	6.8	47.22	82.48	129.70
5	9.8	64.82	113.21	178.02
6	13.3	83.78	146.32	230.10
7	17.1	102.58	179.17	281.75
8	21.4	122.26	213.55	335.81
9	26.0	141.47	247.09	388.57
10	31.0	160.65	280.58	441.23
11	36.4	179.65	313.77	493.42
12	42.2	198.35	346.44	544.80
13	48.3	216.22	377.64	593.86
14	54.7	233.21	407.31	640.52
15	61.5	249.71	436.14	685.85
16	68.6	265.28	463.33	728.60
17	76.0	279.90	488.86	768.76
18	83.7	293.58	512.76	806.33
19	91.7	306.32	535.01	841.33
20	100.0	318.14	555.66	873.79
20-Year Total		3,320.88	5,800.23	9,121.11
Equiv. Ann. Tot.		266.48	465.43	731.90

APPENDIX

Appendix A: MicroBENCOST Output - Rural 2-Lane Undivided

Appendix B: MicroBENCOST Output - Urban Freeway

Appendix C: MicroBENCOST Output - Rural Divided Binder Problem

Appendix D: MicroBENCOST Output - Urban Freeway Binder Problem

Appendix E: MicroBENCOST Output - Urban 4-Lane Divided

Appendix F: MicroBENCOST Output - Urban 2-Lane Undivided

Appendix G: MicroBENCOST Output - Rural Freeway

Appendix H: MicroBENCOST Output - Rural 4-Lane Divided

Appendix I: MicroBENCOST Input - Urban Freeway

Appendix J: MicroBENCOST Input - Urban 4-Lane Divided

Appendix K: MicroBENCOST Input - Urban 2-Lane Undivided

Appendix L: MicroBENCOST Input - Rural Freeway

Appendix M: MicroBENCOST Input - Rural 4-Lane Divided

Appendix N: MicroBENCOST Input - Rural 2-Lane Undivided

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